MODERNIST CUISINE

2 · Techniques and Equipment

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MODERNIST CUISINE

The Art and Science of Cooking

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Volume 2

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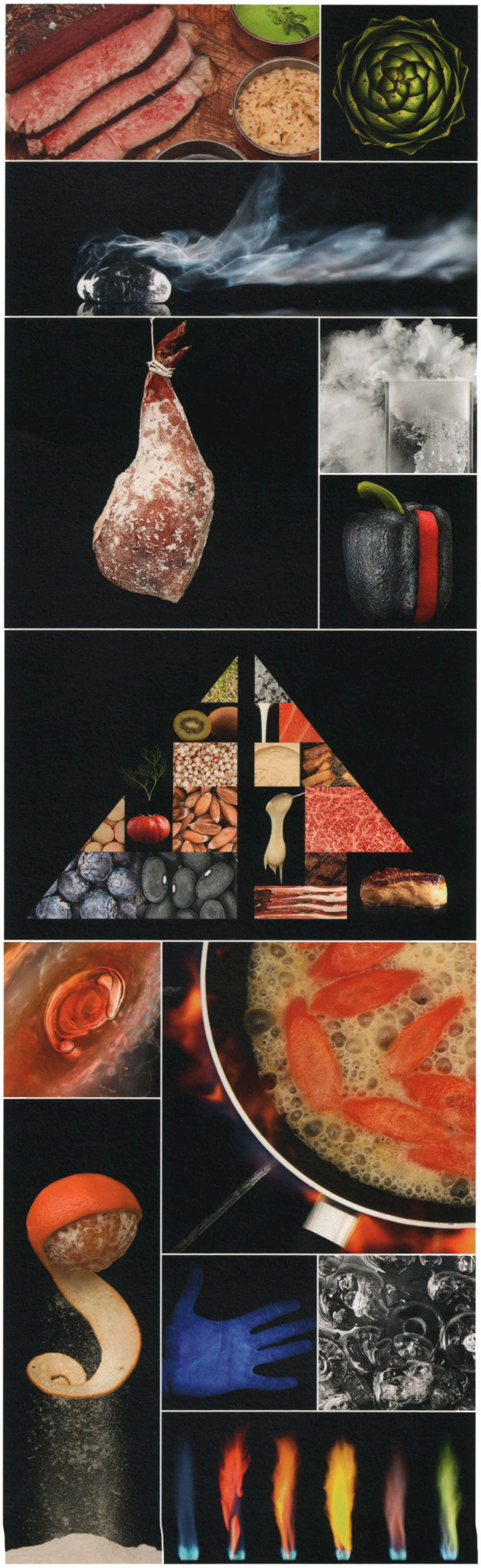
VOLUME 1: HISTORY AND FUNDAMENTALS



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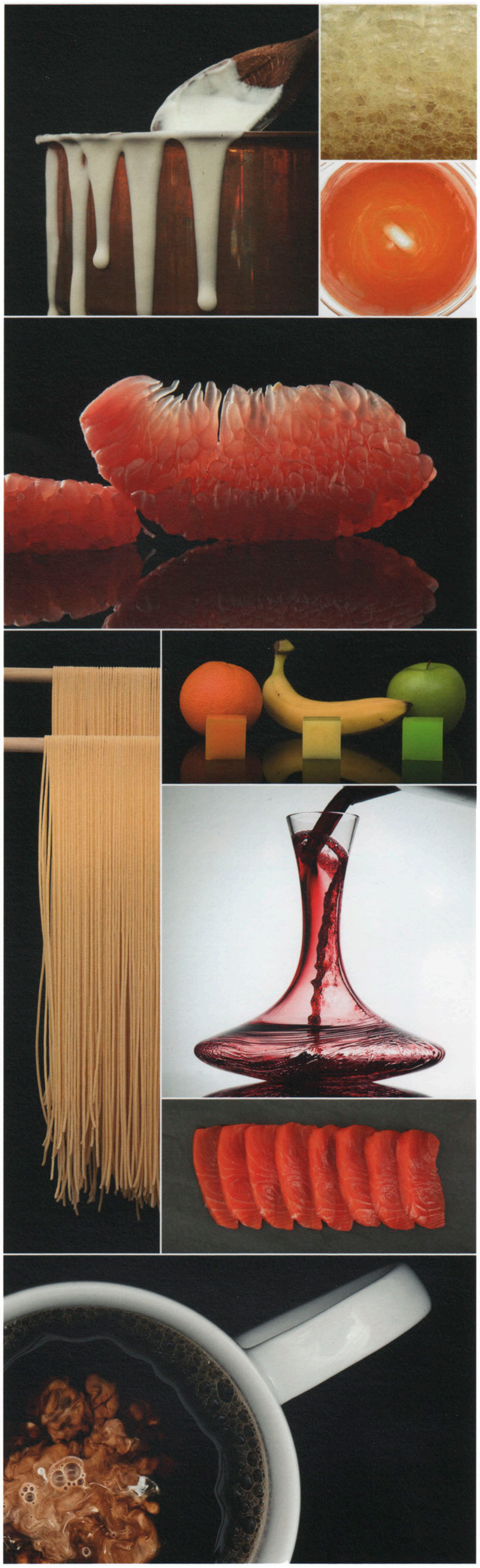

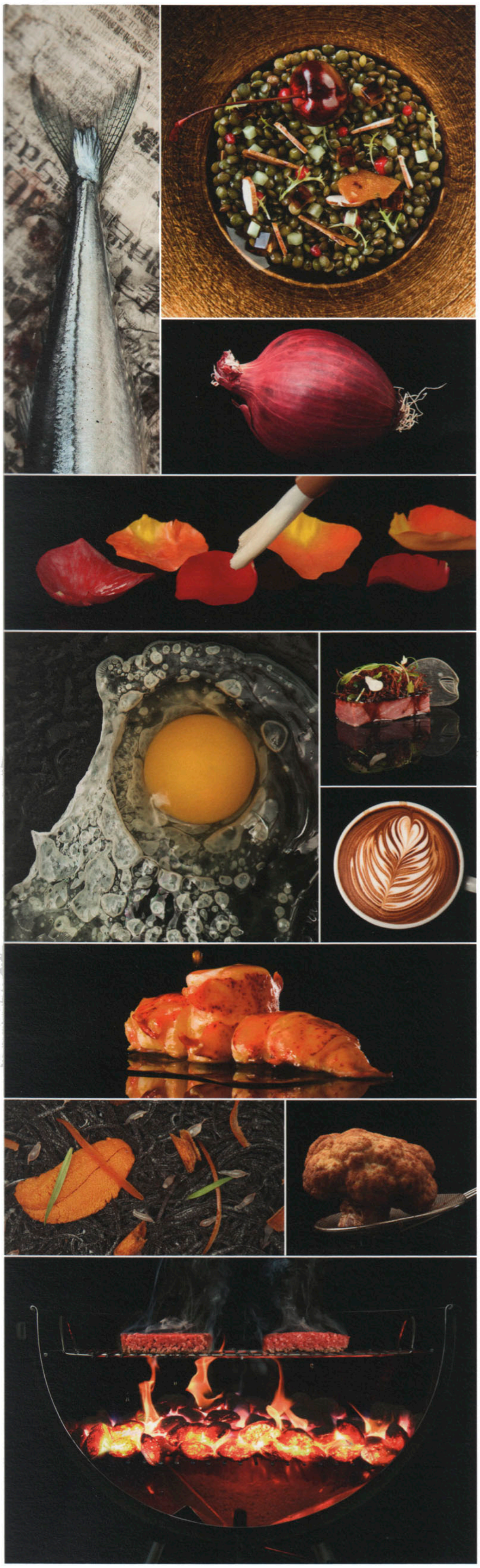

7 TRADITIONAL COOKING

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TRADITIONAL COOKING

Cooking is as old as humanity itself—it may even have shaped our anatomy. Our large brains, small mouths, dull teeth, and narrow pelvises can all be traced to *Homo sapiens's* taming of fire as a tool to convert raw food to cooked. When we bake a loaf of bread, roast a leg of lamb, or even flip a burger on the grill, we're invoking time-honored techniques passed down not only from generation to generation but from the dawn of the species. These traditional methods of cooking have become as familiar and comfortable as our own kitchens.

So it may come as a surprise to learn how traditional cooking techniques actually work—and don't work. The practices are enshrined in centuries of folk wisdom that, quite frankly, isn't always accurate. Baking, for example, wasn't originally about getting things hot; it was about drying things out. Raising the height of a grill won't significantly lower the heat that's irradiating your food. Deep-frying is more closely related to baking than it is to panfrying. And although it's true that steam is hotter than boiling water, boiling water often cooks food faster than steam. Skeptical? Read on. We can prove it.

What's more, many of the cooking techniques that we think of as traditional have evolved considerably in recent history. The braising and pot-roasting of the 17th century are extinct today; contemporary braising is actually stewing, but no one recognizes the difference in taste because we lack a point of comparison. Smoking has been transformed from a technique for preserving food into a technique for flavoring food. Oil is not essential for making a transcendent confit.

All of these techniques are worth a closer look because a deeper understanding of the scientific principles involved in each empowers you to perfect them. If you know how the masters control the heat of a sauté or a wok by keeping food constantly in motion, you're that much closer to achieving their results. Knowing the science of traditional cooking can save money and effort, too. You'll learn, among other things, that fancy copper pans can't compensate for a bum burner. In these and many other examples, we've found that it's worth reconsidering some of our most cherished notions about the cooking traditions we thought we knew.

Pit steaming, still used in traditional imu cooking in Hawaii (far left), is an archaic form of cooking that combines elements of several traditional techniques—including baking, steaming, and roasting—to achieve a unique result (left). A peek inside a pot roast in progress (opening photo) reveals the many ways in which even the simplest cooking methods transfer heat to food. For more details, see The Lost Art of Pot-Roasting, page 94.

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GRILLING

Older than humanity itself, grilling was *the* cooking technique that set our primate ancestors on the evolutionary path to becoming civilized humans. The ability to conquer and control fire distinguished *Homo erectus* from other animals and allowed the most basic level of culinary refinement. Little wonder, then, that our craving for the flavor of food charred over an open flame is practically universal.

Our ancestors must have fast discovered that cooking over towering flames is for the less evolved and that grilling is best done over the glowing coals of a dying fire. No doubt they also soon discovered that building a fire and waiting for it to burn down is time-consuming. With the invention of charcoal some 30,000 years ago, primitive man learned to circumvent this step.

Charcoal has many advantages: it burns cleaner and hotter than wood, it burns more evenly and longer than wood, and it can be made from materials other than wood—a useful attribute when firewood is scarce. For early humans, its usefulness extended beyond cooking. The slow, steady burn provided intense heat for the smelting and working of metals, and the spent coals became drawing tools for the cave art that marked the beginnings of pictographic knowledge. Indeed, the virtues of charcoal are so numerous that it is no exaggeration to say that if cooking with fire was the technology that made us human, charcoal was the technology that gave us civilization.

Charcoal also gives the cook greater control over heat than open flames allow. To understand why, you need to know how a chimney works. Fire is the engine that drives air up a chimney. The flames and hot coals heat the surrounding air, causing it to expand and become more buoyant. The heated air floats to the top of the chimney like a stream of bubbles rising through water. Stoke the fire, and the hot air flows faster; choke the fire, and the flow of hot air slows. The flow of air is called the **draft,** and it's directly related to the intensity of the heat from a fire.

Just as the draft is controlled by the fire, the fire can also be controlled by the draft. To burn, fire needs oxygen; indeed, it consumes oxygen much more quickly than it does coal. The draft pulls oxygen into the fire: as hot, oxygen-poor air rushes up and away, cooler, oxygen-rich air flows in to replace it. Increase the draft, and you will thus make the fire burn faster and hotter; dampening the draft slows the fire and cools it.

Watch a master griller stoke a fire, and you'll see him rake coals around or perhaps adjust a vent under the grill. Rarely will you see him add more coals. Instead, he's making the fire hotter by increasing the amount of draft. Slowing the draft, in contrast, starves the fire of oxygen; reduce the draft too much, and the fire will smolder.

If you can control the draft, you can exert masterful control over the heat of a charcoal grill—once you can get the hang of the lag in response. Hot coals cool slowly, so you must adjust the draft well before you want the temperature to drop. Experience builds an intuition for this, which some have called the art of the grill.

Direct grilling can produce heat so intense that the skin of a pepper chars before the interior is fully cooked. Only by understanding the counterintuitive ways in which radiant heat works can you master the art of the grill.

IRRADIATING FOOD TO PERFECTION

Grilling food over an open flame is a practice as old as humanity itself. Indeed, it's likely that we are human precisely because we learned to grill our food. Perhaps it is this primeval connection that makes grilled foods such as hamburgers so mouth-watering: we're hard-wired by evolution to find comfort in the heat of the grill, the smell of the smoke, and the taste of the food. Although grilling food is so simple that our ancestors managed to do it eons ago, mastering the heat of the grill is a culinary challenge of the highest order.

Wafting smoke gives form to the turbulent air that rushes skyward past the patties, much like what happens in a chimney. Heat from the burning fuel causes adjacent air to expand, making it more buoyant. As the hot air rises, it cooks the food and creates a draft that sucks more air in to fuel the fire.

Food must be relatively thin to cook properly in the intense radiant heat and scorching air rising from the coals. Food that is too thick will burn on the outside before heat can penetrate to its core.

A layer of ash should coat the coals before food goes on the grill. The ash dims the coals' glow, moderating the heat they radiate. The ash also reduces the chimney effect by insulating the coals from the air.

A variable air vent allows the griller to control the flow of air into the fire. Starve the coals of fresh air to cool them and slow the chimney effect; open the vents to turn up the heat.

Most of the heat a grill produces is wasted. It bypasses the food and literally goes up in smoke or is radiated away into the sky. But without the intense heat, grilled food would not taste as good.

Smoke is an aerosol—a mixture of minuscule solid particles and liquid droplets dispersed within a blend of invisible gases. The solids make smoke heavier than air; it floats only when carried aloft by rising hot air from the draft. If you let smoke cool to ambient temperature, it will sink. The solids also scatter light—an example of the so-called Tyndall effect—and blue rays get scattered more than red, casting smoke's blue haze (see page 124).

Grills are definitely *not* nonstick surfaces. The high temperatures at which charcoal grills operate would make most nonstick coatings unstable. Coating food in oil works, but can cause flare-ups that coat the food with soot. The best way to avoid sticking is to preseason the grill with a patina much as you would an iron skillet or steel wok (see How to Season a Wok, page 53).

Drippings are the real secret to the unique flavor of grilled food. As these complex chemical solutions combust, they coat the food with a panoply of aromatic and delicious compounds.

Flames may seem to flicker above charcoal, but these fiery tongues are actually little plumes of incandescent carbon soot. The superheated air is turbulent; it lifts soot particles off the coals and allows them to react with carbon dioxide in the air to produce carbon monoxide. The flammable monoxide burns with a hot but faint blue flame at 1,600 °C / 2,900 °F or higher, which heats the soot particles so much that they glow with an intense white light that masks the dim fire from the monoxide.

Glowing coals generate temperatures well above the 700 °C / 1,300 °F required to emit light in the visible part of the spectrum. The bright orange light emitted by the center of the embers indicates a temperature above 1,100 °C / 2,000 °F. Pockets between the coals are hotter still: there, burning carbon monoxide heats soot to at least 1,400 °C / 2,550 °F!

Charcoal vs. Gas: Lies, Damn Lies, and BTUs

Charcoal grills may be traditional, but gas grills offer such convenience that they have become vastly more popular. Gas grill manufacturers love to quote the British thermal unit (BTU) power ratings for their grills. A single number reduces the complexities of comparison shopping to "bigger is better."

Here's the problem: the BTU is not a unit of power. It's a unit of energy, like the calorie and the joule. Marketers erroneously use the BTU as lazy shorthand for the unit of power that they actually mean, the BTU/h (or its metric counterpart, the watt), which measures the amount of energy delivered over time.

With this confusion cleared up, the question is, do BTU ratings matter? The unequivocal answer is no. BTU ratings do not matter. What does matter is the **intensity** of the power: how much power is delivered to each square inch (or square centimeter) of grill surface. This is the **heat flux** from a grill, and it is what does the searing and cooking. Quoting the peak performance of a grill in BTU/h · in² (or W/cm²) allows you to compare one grill with another. Manufacturers apparently see no advantage in advertising these numbers. But that's okay because calculating the peak heat flux for a gas grill is straightforward: simply divide the maximum power rating given by the manufacturer by the area of the grill.

Charcoal grills are not so easy to analyze. Coaxing maximum power from a charcoal grill takes experience and skill. Hence charcoal grill manufacturers don't bother to provide power ratings, which vary with the talent of the person manning the fire. But even without the numbers to quantify power precisely, experienced grill cooks know that gas grills simply wilt by comparison with charcoal grills. But why?

The surprising answer is that charcoal fires deliver more heat to the grill because they burn *cooler* and *dirtier* than gas flames do. Confusing, perhaps, but true.

To understand how this works, think about how the cooking heat arrives at the food. Yes, hot air rushes past the grill—this is the chimney effect described on the previous page. But hot air convection is not what sears your steak. Most of the energy in that rising air is wasted as it flies by without ever making contact with the food. Rather, it is intense **radiant heat** that quickly browns the meat. Charcoal grills simply radiate more heat than do gas grills of comparable size.

To compare one grill with another, calculate the heat flux of each one. First, take the grill power (in BTU/h or watts), then divide it by the grill area (in in² or cm²) to obtain the heat flux. For example:

$$\begin{array}{l} 100{,}000\ \text{BTU/h} \\ \underline{\div\ 1{,}000\ \text{in}^2} \\ =100\ \text{BTU/h}\cdot\text{in}^2 \end{array}$$

$$\begin{array}{l} 29{,}300\ \text{W} \\ \underline{\div\ 6{,}500\ \text{cm}^2} \\ =4.5\ \text{W/cm}^2 \end{array}$$

Heat flux, of course, tells you nothing about important real-world factors such as the hot and cold spots of a grill. For more on the evenness of grills, see The Sweet Spot of a Grill, page 14.

Beneath a very light coating of ash, this hardwood charcoal is radiating heat with incandescent intensity. Although the temperature of the glowing charcoal is significantly cooler than that of burning gas, it radiates heat with an intensity much greater than can be mustered by all but a few exotic catalytic gas grills. That's why charcoal has an unrivaled ability to quickly sear food on a grill.

Once the flames and smoke of initial combustion burn off the charcoal, they leave behind red-hot coals made from nothing more than carbon and ash. Note that the coals do not burn, exactly: they glow. Supplied with ample oxygen, the carbon in charcoal chemically reacts with the oxygen to form carbon dioxide, which reacts in turn with the charcoal to form carbon monoxide. These chemical rearrangements release lots of heat, which raises the temperature of the charcoal. The higher temperature then speeds the chemical reactions, forming yet more carbon monoxide and releasing yet more heat. Eventually, the coals reach temperatures near 1,100 °C / 2,000 °F—hot enough that they glow with the visible orange luminance of blackbody radiation.

Propane and natural gas burn at a much hotter temperature, around 1,900 °C / 3,500 °F. The main chemical reaction involved in their combustion is fundamentally different from that in glowing coals, however. Gas burns cleanly in flames that visibly emit only an ethereal blue light. Although the temperature inside those dim blue flames is quite high, they actually radiate very little energy.

Gas grill manufacturers understand the importance of radiant heat, and they know that clean-burning gas doesn't produce much of it. They overcome this difficulty by converting some of the hot gases of combustion into radiant heat by placing lava rocks, ceramic plates, or metal bars above the flames. As these surfaces heat up, they emit radiant heat, but much less of it than glowing charcoal does. Think about it: when was the last time you saw lava rocks on a gas grill glowing with the same brightness as charcoal embers?

As the hot gases travel from the flame to the radiating surface, they mix with cooler surrounding air. That mixing makes it difficult to raise the temperature of the radiant emitters in a gas grill to much higher than about 800 °C / 1,500 °F—a good 300 °C / 500 °F below the radiant temperature of glowing charcoal. That is a large difference in effective temperature, and it has a disproportionate effect on radiant heating power.

So although a gas grill at full tilt may produce 5 W/cm^2 (110 BTU/h · in^2) of radiant heat, a charcoal grill can easily deliver more than twice this heat flux, or about 11 W/cm^2 (250 BTU/h · in^2). The awesome radiance of glowing coals is what gives charcoal grills their unrivaled ability to sear in a flash.

For more on blackbody radiation, see Heat Rays, page 1·284.

The amount of heat radiated by the heating elements in a grill increases proportional to the fourth power of the temperature (see page 1·284), so the hotter the element, the higher the heat flux.

Clean-burning gas produces very little radiant heat directly. Gas grill manufacturers overcome this limitation by placing ceramic plates, lava rocks, or metal searing bars between the burner and the grill. The hot gases of combustion heat these objects until they emit a searing radiant heat that does the grilling. These hot surfaces also provide a place for drippings to fall and burn, thus contributing much of the flavor unique to grilling.

THE CHEMISTRY OF
Where There's Smoke, There's Flavor

Two distinct groups swear by charcoal grills: briquette devotees and those who favor hardwood charcoal. Advocates of the pillow-shaped lumps of charcoal cite their ease of use and consistent, steady heat. Grilling purists, on the other hand, point out that honest-to-goodness blackened chunks of hardwood burn hotter, faster, and cleaner. These are all fair points.

Some evangelists for hardwood fuels also claim that charcoal made from hickory, mesquite, or other fragrant-burning woods imparts flavor that is the secret to grilling nirvana. They scoff at briquettes and claim that the only flavor they impart is the taste of lighter fluid. But science tells us that this can be nothing more than zealotry. Once the flames of ignition have died and the coals are glowing hot, neither briquettes nor hardwood charcoals have any flavor left to impart. Any aromatic compounds the fuel once harbored were vaporized and destroyed long before the food was laid on the grill.

The composition of the charcoal does affect its ash content. Briquettes contain more incombustible minerals and thus leave behind a lot of ash. The blanket of ash insulates the embers somewhat but also diffuses their heat, so they burn cooler but also slow and steady. Hardwood charcoal leaves less ash, so it burns hotter but usually faster and less predictably.

Neither of these effects matters to the flavor, however. Carbon is carbon; as it burns, it imparts no flavor of its own to the food being grilled.

The real secret to the flavor of grilled food is not the fuel but the drippings. Dribbles of juice laden with natural sugars, proteins, and oils fall onto the hot coals and burst into smoke and flame. By catalyzing myriad chemical reactions, the intense heat forges these charred juices into molecules that convey the aromas of grilling food. These new molecules literally go up in smoke, coating the food with the unmistakable flavor of grilled food.

The real debate among the faithful, then, shouldn't be about which charcoal is best. It should be about whether charcoal is necessary at all.

A setup that can quickly raise the grill is the best way to handle flare-ups Dodging the flames works better than dousing them with a spritz of water from a spray bottle. However, raising the grill doesn't reduce the intensity of the radiant heat. To make an appreciable difference in the intensity of the heat, you must raise the grill surprisingly high above the coals. This is explained in The Sweet Spot of a Grill, on page 14.

BAKING ON THE BARBIE

When grilling large or thick foods, sometimes the best approach is to turn the grill into an oven through indirect grilling. After a quick sear over the coals, shift the food to one side, push the coals to the other side, and cover the grill with a lid. This technique prevents the intense heat of direct grilling from burning the surface of the food before the interior is fully cooked. Instead, the food bakes at a lower temperature.

A drawback to indirect grilling is that a covered grill makes a mediocre oven: the heat inside is uneven and difficult to control. Food cooked this way also lacks that mouth-watering grilled flavor because drippings don't fall on the hot coals. Some cooks toss wood chips onto the coals to add smoke flavor to the food. Another option is to leave a few meat trimmings above the coals to drizzle juices onto the embers; the flavorful smoke then permeates the food baking on the other side of the grill.

A pan of water under the food will humidify the circulating hot air and raise the wet-bulb temperature. This addition effectively accelerates heat transfer into the food, so cooking finishes faster than it would in dry air. Adding moisture to the air also slows the evaporation of juices from the food, so it retains more of its succulence (see Baking, page 101).

A tight-fitting lid traps hot air that bakes the food. The lid also cuts off the supply of fresh air and thus starves the fire and lowers the cooking temperature.

A sputtering fire can cause the temperature inside the grill to fluctuate.

The Sweet Spot of a Grill

Direct grilling happens fast, and a fire that gets ahead of you all but guarantees burnt food. The great challenge of grilling is thus controlling the intensity of the heat experienced by each part of the food. To do this on a gas grill, you twist knobs on the burner controls. On a charcoal grill, you adjust the flue to enliven or suffocate the embers, and you also time the cooking so an appropriately thick blanket of ash covers the coals and tempers the intensity of their radiant heat. On every kind of grill, you must turn the food at appropriate moments to even out the cooking.

For more on the physics of radiant heat, see chapter 5 on Heat and Energy, page 1·260.

Those are the basics for which most grillers have some intuition. But to truly master grilling requires a new perspective. We mean this quite literally—if you want to understand why some grills cook faster than others, why grill size matters, and how to find that sweet spot on your grill where the food cooks best, you must look at grilling from the food's point of view.

Remember that most of the heat produced by a grill hits the food in radiant form as rays of light. The light is primarily in the infrared part of the spectrum and thus invisible, but a hand held above the coals perceives it well enough. Like visible light rays, infrared heat rays travel outward from their source in every direction, following straight paths until they are absorbed by a dark surface or reflected by something shiny. Unlike the hot bits of matter that transmit heat by convection or conduction, rays of heat do not flow around obstacles. Beams of heat thus cast shadows of coolness, just as beams of light cast ordinary shadows.

The light-like behavior of radiant heat has surprising consequences for grilling. It means that there is no truth to the common claim that you can slow the cooking by raising the food a little higher above the coals. It also means that black is a terrible color for a grill and that the ubiquitous kettle shape is among the worst possible. Once you have intuition for the behavior of radiant heat, you'll want a cooker that has a large bed of coals, straight sides, and a shiny interior.

To understand why, imagine replacing the bed of coals in your charcoal grill (or the radiating elements in a gas grill) with a flat, fluorescent light panel of the same size and with the light shining upward. Now imagine that you are a steak (or, if you prefer, a pepper) lying face down on the grill 1 cm / ½ in above the lamp. Looking down, you see light flooding up at you from every direction. Unless the cooker is tiny, you can no more see the edge of the lamp than a person looking down at his feet can perceive the horizon.

Let's say the cook raises the grill to 10 cm / 4 in above the lamp. Now what do you see below you? The view at this height is almost precisely the same as before. Assuming the lamp has a modest width of at least 56 cm / 22 in, it occupies nearly your entire field of vision even at this distance.

So it is for radiant heat as well. What matters to the food is how much of its view is filled by glowing

A black, hibachi-style grill cooks unevenly near the side walls because the dark cast iron absorbs the radiant heat of the coals. Lining the sides with reflective aluminum foil causes radiant heat from the coals to bounce upward and heat the food near the edges of the grill more evenly.

Getting a big sweet spot with the ubiquitous kettle grill is hopeless. Even lining the sides with aluminum foil won't help because the reflecting angles are all wrong. The only solution is to use a ring of metal to create vertical reflecting sides.

coals or hot burner elements. That perspective changes slowly with distance. As a result, the intensity of heat that the food receives from the coals does not fall in any meaningful way until the food is at a much farther distance from the heat source than any commercial grill can attain.

Every grill has a critical distance from the coals; food at that distance or closer experiences the full intensity of the grill's heat. The critical distance is equal to 18.5% of the width of the grill if its sides do not reflect heat. For grills with reflective sides, the critical distance is 37% of the width.

As the 50% line on the graph on page 16 illustrates, to knock the heat down by half on a grill that is 1.2 m / 4 ft wide, you must raise the food to a height equal to more than one-half the grill width—a whopping 66 cm / 26 in above the coals! For a grill this size, food at a height of 23 cm / 9 in experiences, for all practical purposes, heat just as intense as it would if the food were sitting right next to the coals.

The inescapable conclusion is that using distance to slow the cooking really only works in rotisseries or when using spit-roasting techniques, such as the Argentinean *asado,* that keep the food far from the fire.

Point of view also determines how consistent the heat is from the center of the grill to its edges. The extent of this horizontal sweet spot and how rapidly the heat collapses at its edges depends on three major factors. The first two variables—the size of the grill and the height of the food above the glowing coals or burner elements—are hardly surprising. Think again about looking down from the grill at a fluorescent lamp in the bottom of the cooker. The bigger the lamp and the closer you are to it, the farther off center you can move before the light ceases to dominate your field of view.

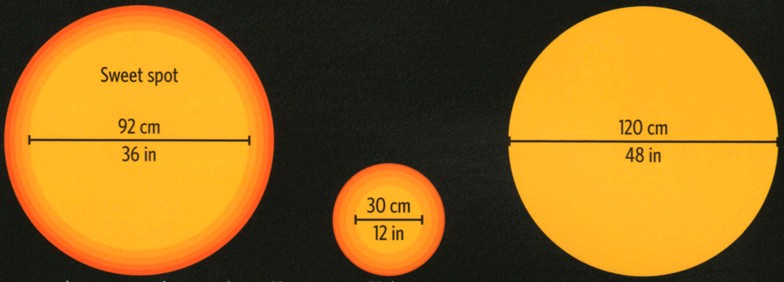
A third, equally crucial factor is much less widely appreciated: it is how well the sides of the grill *reflect* the heat rays. Just as restaurant owners sometimes install a large mirror on one wall to make a small dining room appear twice its actual size, a reflective surface on the side of a grill can make the burner surface or bed of coals appear (to the food) much bigger than it really is. Indeed, if all sides of the grill reflect infrared heat rays, the food is effectively in a hall of mirrors that makes the heat source appear to extend infinitely.

Reflective sides can extend the sweet spot to cover about 90% of the extent of the grill, which makes it much easier to get even cooking across the entire grill surface. So it is unfortunate that many grills are painted black on the inside and are thus almost completely nonreflective. The good news is that you can easily and dramatically improve the performance of a mediocre black grill for a few dollars. Just install a simple reflector: a vertical wall at the edges of the grill made from shiny polished metal. Aluminum foil works reasonably well. Keep it clean, and enjoy cooking in your newly enlarged sweet spot!

Another easy way to knock down the heat coming off a bed of coals is to cover the grill with aluminum foil, then put the food on the foil. The shiny surface will reflect the radiant heat back down, preventing the food from scorching. It also helps prevent drippings from flaring up. On the other hand, it blocks the flavor that flare-ups provide.

HOW TO Find the Sweet Spot

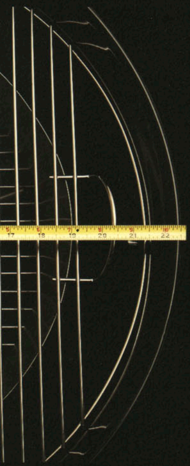
Because most of the heat grills deliver to food is in the form of radiation, not hot air, the speed at which cooking occurs can change in counterintuitive ways as you raise the food above the coals or move the food toward the edges of the grill. To understand how your grill works, follow the steps below to calculate how far the central sweet spot of consistent heat extends and how heat intensity falls off with height.



Large (122 cm / 48 in) grill with dark sides

Small (51 cm / 20 in) grill

Large grill with reflective sides



In the sweet spot, the intensity of the heat delivered to the food varies by no more than 10% of its level at dead center. How quickly the heat falls off depends on the width of the heat source, the height of the food above it, and how well the sides of the grill reflect heat. In a large, nonreflective cooker with coals that extend 120 cm / 48 in and a grill set 10 cm / 4 in above the coals, the sweet spot covers 59% of the grill area (left circle). The sweet spot at that same height shrinks to 36% in a smaller grill that is just 50 cm / 20 in wide (middle circle). But it expands to include the entire grill if the sides reflect heat (right circle).

1 **Measure the width.** Take the dimension of the heat source: the bed of coals of a charcoal grill or the heat-radiating elements of a gas grill. Measure the diameter if your grill is round; otherwise, use the longest horizontal dimension. (Example: width = 50 cm)

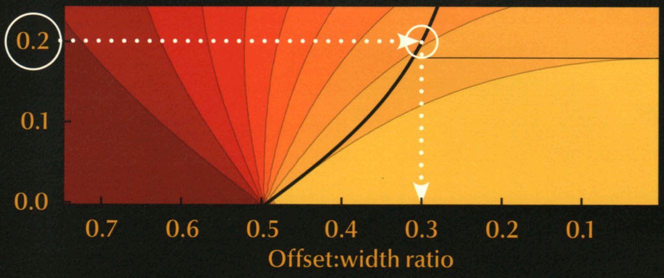
3 **Calculate the height:width ratio.** Divide the height by the width. (Example: 10 cm ÷ 50 cm = 0.2)

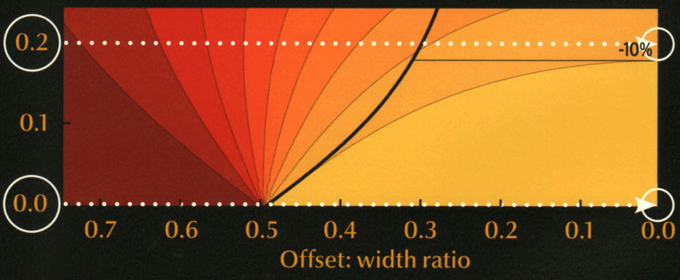
4 **Use the chart.** To determine the size of the sweet spot as a fraction of the grill width, first find the height:width ratio on the vertical axis of the graph on the next page. Draw a straight line from that point to the thick black curve that marks the left-hand boundary of the sweet spot (right). Then draw a straight line from the intersection with the curve to the horizontal axis. Note the value of the offset:width ratio. (In the example at right, the offset:width ratio is 0.3.)

5 **Convert to familiar units.** To determine how far the sweet spot extends from the center of the grill in centimeters or inches, multiply the offset:width ratio by the width of the heat source. (Example: 0.3 × 50 cm = 15 cm. Food placed within 15 cm / 6 in of the center of the grill will thus fall within the sweet spot and will experience no more than a 10% variation in heat intensity.)

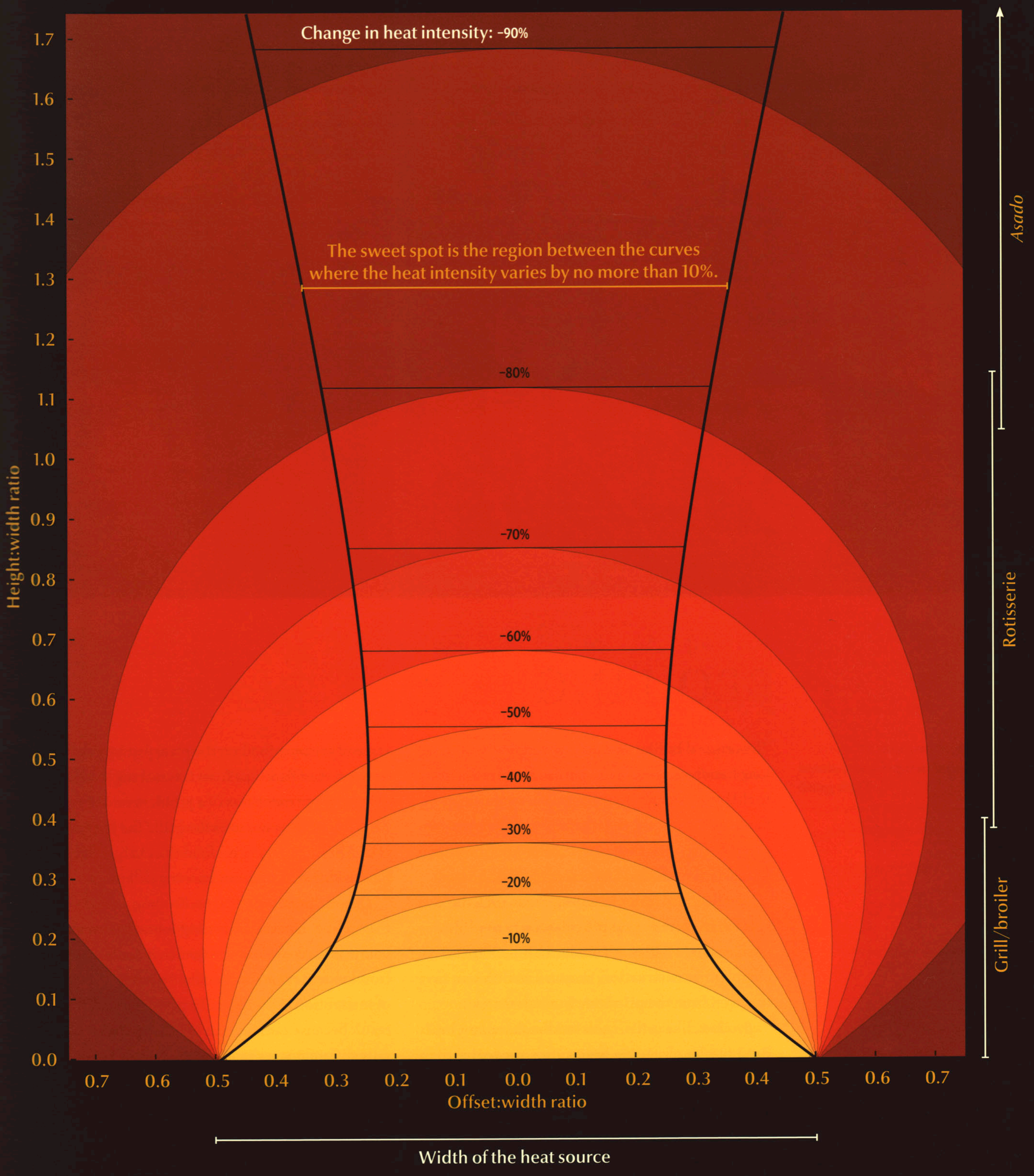
6 **Check the effect of raising the grill (optional).** If the height of your grill is adjustable, follow steps 2 and 3 for both the highest and the lowest positions. Then draw a horizontal line from each height:width ratio value to the center of the chart (above right). Estimate the change in intensity using the black percentages as a guide.

2 **Measure the height.** Take the vertical distance from the food to the heat source at the center of the grill. If the grill height is adjustable, use a middle setting. (Example: height = 10 cm)





(Example: If the grill adjusts from 10 cm to 2 cm, the height:width ratio ranges from 0.2 to 0.04 (2 cm ÷ 50 cm = 0.04), and the change in intensity due to height varies from −12% to −2%. This small difference probably has minimal effects on the food.)


The sweet spot is the region between the curves where the heat intensity varies by no more than 10%.

Broiling is an excellent way to quickly char a tuna steak, brown the top of a gratin, or crisp a leg of duck confit. But broiling evenly requires finesse.

BROILING

The original broiler was just an iron disc with a long handle. Known as a salamander (a reference to this amphibian's mythical connection with flames), it was stuck into the heart of a fire until it glowed. The cook then held the red-hot iron near the surface of the food to sear it. Today, the term salamander has become synonymous with the specialized broiler that provides a way to grill upside-down. Although modern broilers are more complex in construction, they are no different in function from the primitive iron salamander.

Broilers, like grills, cook food with radiant heat. But a broiler places the heat source above the food—an arrangement that sometimes offers a great advantage. Broilers can easily brown the surface of foods that would be difficult, if not impossible, to brown over a grill or on a range. The broiler offers a convenient tool for quickly browning and crisping food on the plate just before serving. And flare-ups from fat- and sugar-laden drippings are much less of a problem under a broiler than they are over the grill. The downside is that broilers don't give food the chargrilled flavors that waft up from burning drippings.

Despite these advantages, broiling can be frustrating. Uneven browning is one common complaint. Another is the tendency for foods to go from underdone to burned in the briefest moment of inattention. As with grilling, these problems result because radiant heat behaves in fundamentally different ways than conductive and convective heat do. You are cooking food with invisible (infrared) light, and it is hard to develop an intuition for a process so far removed from tangible experience.

Some rules of thumb can help. Every broiler,

like every grill, has a sweet spot—or perhaps we should call it a sweet zone. Place the food above or below this zone, and it will cook unevenly. The intensity of the heat is also at its maximum in the sweet zone. There is no point in raising the food any closer to the heating elements because moving the food higher won't make it any hotter; it will simply make the cooking more uneven.

You can find the height of the sweet zone in your own oven with a bit of trial and error or by applying some simple math (see Grilling from the Top Down, page 22).

Another important detail to keep in mind is that if your broiler is open on the sides, the heating will diminish appreciably toward the edges. So don't let the food get too close to the perimeter. If you want to make a broiler cook evenly near the edges, install shiny vertical reflectors on the sides; these will bounce the heat rays back toward the food, effectively making the heating element look (to the food) much larger than it actually is. If reflectors are not an option, set the food in a baking dish lined with reflective foil.

Finally, it's not the imagination of the hapless cook that his gratin burned under the broiler the second he looked away. Shiny or light-colored surfaces, like fish skin or a béchamel glaze on a gratin, tend to reflect and scatter most of the incoming infrared radiation. That means they absorb only a small fraction of the radiant energy, so they heat slowly. Conversely, dark surfaces heat quickly because they scatter less radiation and thus absorb most of the incoming energy.

The tricky part, of course, is that many foods change from light to dark as they cook. Think of a marshmallow toasting over a campfire and how

For more on the phenomena that cause heat intensity to be strongest in the sweet zone, see Grilling, page 7.

quickly it can go from white to brown to flaming. A broiler can similarly burn food that moments earlier hadn't even started to toast. Cooking goes slowly at first because most of the incoming energy bounces off the surface, which heats gradually. Then, as browning reactions begin, the darkening surface rapidly soaks up more and more of the heat rays. The increase in temperature accelerates dramatically. If you aren't watching, the food will go from golden brown to charred black before you know it.

How Broilers Work

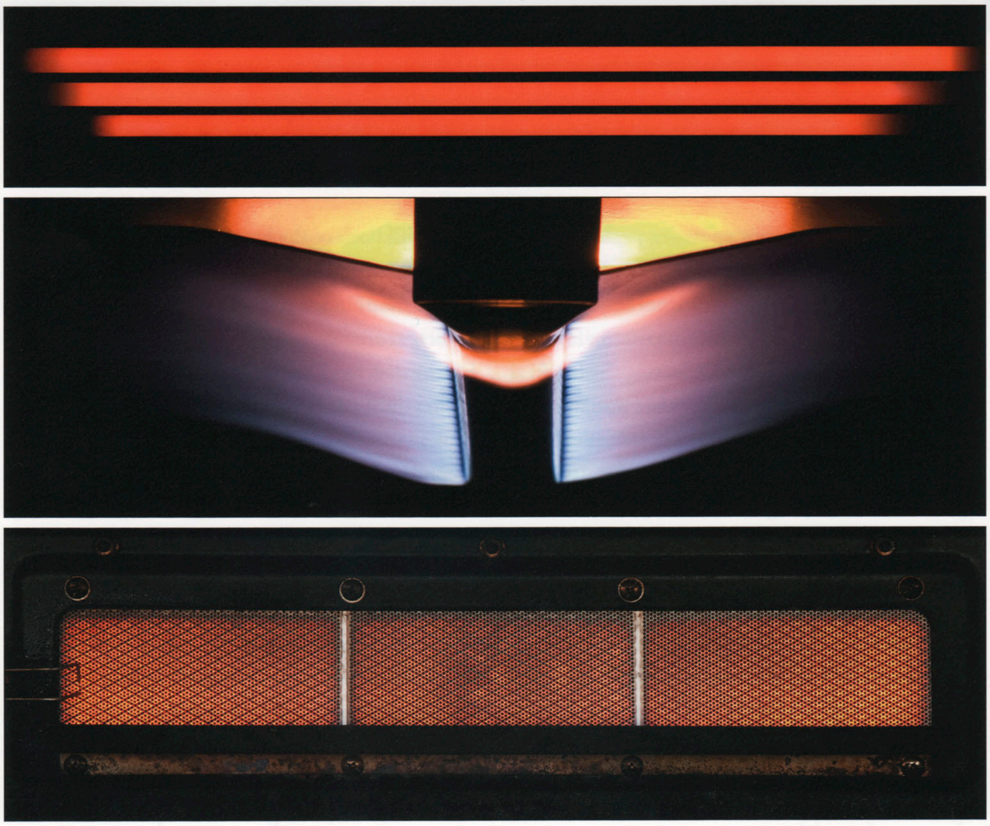
If you stay alert, though, you can avoid such pitfalls and use broiling to great advantage, particularly if you have good equipment. The features that make for a high-quality unit depend on whether the broiler generates its radiant heat with electricity or with gas.

Nearly all gas broilers work a lot like the ancestral salamander. They spread flames across a diffusing plate, which is often made of steel. Eventually the plate becomes hot enough to emit a large amount of radiant heat. This approach works, but it is very inefficient. Most of the burned gas needlessly heats air rather than raising the temperature of the diffusing plate. These broilers thus produce less radiant heat than an electric broiler can with the same amount of energy.

Catalysis offers a far more efficient way to generate radiant heat with gas. Although catalytic broilers are still somewhat exotic and so more expensive than other broilers, they are beginning to appear in professional kitchens and some high-end consumer ovens. Catalytic broilers don't actually burn gas. Instead, they push gas through a porous ceramic plate that is either impregnated with a metal catalyst or covered by a mesh of catalytic metal. When the gas mixes with air near the catalyst, it oxidizes to generate heat, water vapor, and carbon dioxide. This reaction happens inside the pores of the ceramic plate or right on its surface. The plate readily absorbs the heat, then radiates this energy onto the food below.

It may seem counterintuitive, but the ceramic plate never actually gets hot enough to ignite the gas. In other words, catalytic gas broilers are

Three Kinds of Broilers



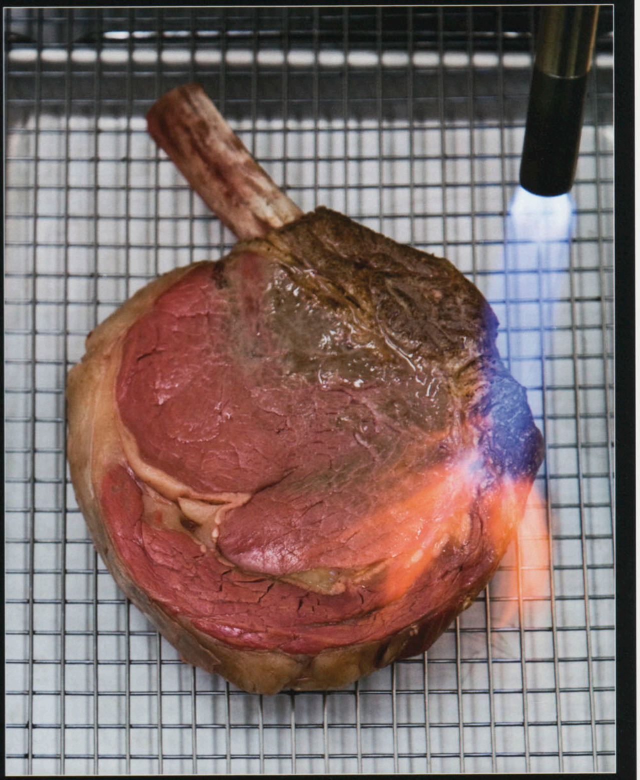
The electric broiler (top) is ubiquitous and reliable. Browning food evenly under one can be tricky, however. Home ovens fitted with electric broilers have an additional deficiency: to avoid overheating the oven, they cycle on and off every few minutes, which can be annoying.

A newer design for the electric broiler has improved the evenness of the radiant heat by dispensing with the glowing rods altogether. Instead the newest electric broilers embed a large number of small electric coils in a ceramic plate. These coils quickly heat the plate, which in turn emits radiant heat evenly. This approach mimics the operation of traditional gas broilers (middle), in which flames from a burner heat a conductive surface that then radiates heat fairly evenly.

A catalytic gas broiler (bottom) avoids burning the gas at all. Instead, it forces gas through a ceramic plate covered by a catalytic mesh. The gas reacts but never combusts, and it efficiently generates a large amount of heat, which the glowing ceramic plate then radiates evenly.

THE TECHNIQUE OF

How Not to Use a Blowtorch



Some chefs tend to use a blowtorch as a kind of portable broiler. These handheld heat sources work very differently from normal broilers, however, because they don't cook with radiant heat. To prove this to yourself, bring your hand close to the flame from the side (carefully!). Note that you can nearly touch the flame before your hand really feels the heat. You can't put your hand anywhere near that close to the front of the flame without burning yourself.

Blowtorches rely on convective heat transfer from fast-moving, very hot gases. The bigger the difference in temperature between the flame and the food, the faster the heat moves from one to the other. With a blowtorch, that difference is huge—around 1,900 °C / 3,400 °F—hence heat strikes the surface of the food really fast. A mechanical effect from the "blow" part of the blowtorch accelerates the heating further. The fast-moving gases whisk away moisture evaporating from the surface of the food being torched. Together, these effects make torching a very fast way indeed to sear a surface.

The convenience comes with a caveat, however: blowtorched food ends up tasting like fuel all too often. Never point the end of a blowtorch at the food before the flame is lit and burning blue. Unburned fuel often squirts from the tip when the torch is first lit; a yellow flame is a telltale sign that the fuel is not being completely burned. Its flavor will be unmistakable—and unpleasant. Get the torch warmed up and adjusted before bringing the flame to the food.

Torches that use MAPP gas burn hotter than those fueled by propane or butane, and they generally contribute no flavor or odor to the food. Oxyacetylene torches are even hotter and are similarly free of odor or flavor transfer issues.

flameless. The heating element hits a maximum temperature around 540 °C / 1,000 °F. This might not seem hot enough to broil effectively, but it still works well enough for browning food. Catalytic broilers are also very energy efficient—they convert about 80% of the chemical energy in the gas to infrared light. And because the ceramic plates are large and heat uniformly, these broilers radiate heat more evenly than conventional broilers do.

Electric broilers are more affordable and more common, however. They use bars or rods made from an alloy of nickel and chromium called nichrome, which heats when electricity passes through it. With reasonable energy efficiency (although nowhere near that of catalytic broilers), electric broilers can heat quickly and reliably to temperatures as high as 2,200 °C / 4,000 °F. Maximum settings are typically restricted to 1,200 °C / 2,200 °F in order to extend the life of the heating element and avoid charring food.

Unfortunately, the typical electric broiler delivers its heat unevenly to most of the oven. Food placed too close to the heating elements develops hot spots directly underneath the rods and cool spots between them. That phenomenon is intuitive enough: if you place your right hand just over a hot grill, it feels the heat much more

A catalyst is a material that acts like a matchmaker: it helps two chemicals (such as methane and oxygen) react faster than they otherwise would, and, after the reaction, it is freed to perform more matches. Catalytic broilers typically use a metal such as platinum as the catalyst.

intensely than your left hand hanging a few inches farther away.

Surprisingly, however, the opposite problem occurs when food is too far from the element: cold spots appear directly below the rods, and the hot spots fall in between the rods! What has changed is that the distance to the element no longer causes heat intensity to vary much from side to side, but reflections do.

If you stand across the room from a fireplace and hold out your hands, the heat on your face and hands feels about the same—the relatively small difference in distance doesn't matter. But the top of the oven reflects heat rays from the upper half of the glowing metal. Food between the rods receives both direct and reflected radiation, whereas food directly beneath the rods cannot "see" the reflections in the top of the oven (see illustration below). Odd as it seems, the food there is shadowed by the heating element itself!

GRILLING FROM THE TOP DOWN

A broiler works like an upside-down grill. A challenge in grilling is to find the sweet spot: the area over which food browns evenly. With broiling, the analogous priority is finding the sweet zone, that ideal separation between the food and the heating elements.

Cooking in the sweet zone is particularly important when using an electric broiler. Place the food too close to the glowing rods or too far away, and part of the food will scorch or cook unevenly. With enough trial and error, you can find the sweet zone of your broiler. But a faster approach is simply to calculate the ideal distance, using the method below.

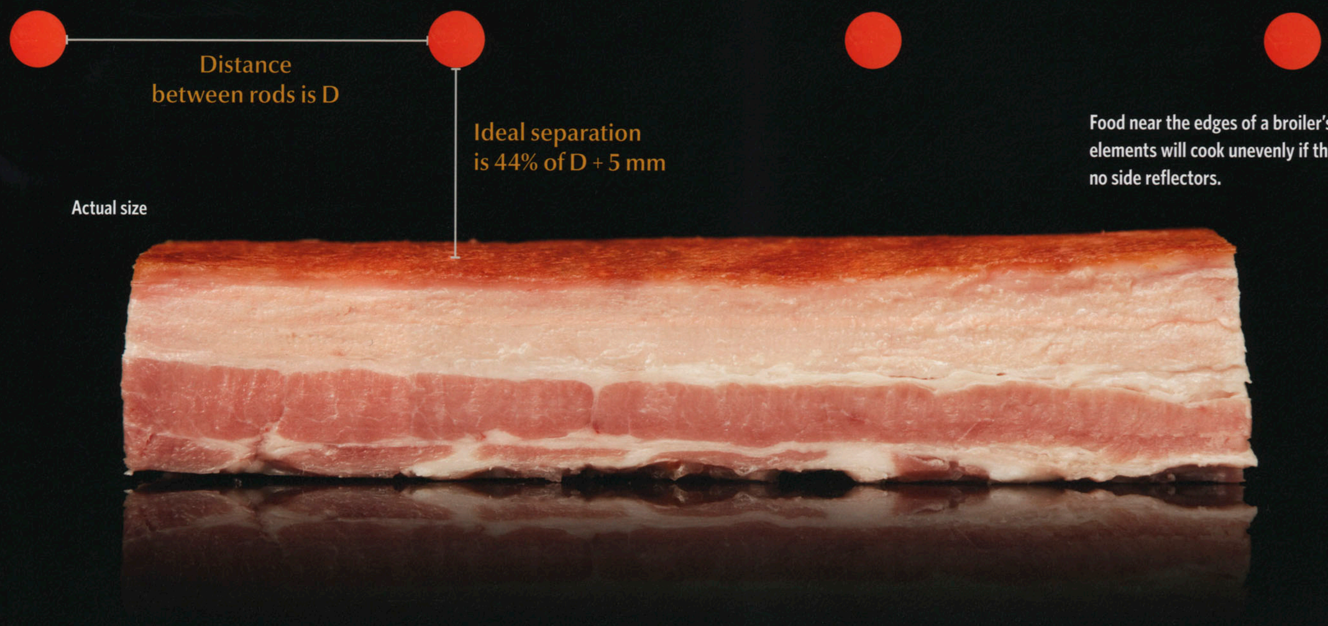
Because the intensity of the heat falls off quickly near the edges of the broiler, it's always a good idea to keep food as close to the center of the broiler as possible. If you can make the sides of your broiler shiny, the reflections will help even out the heat at the margins.

HOW TO Calculate the Sweet Zone of a Broiler

1. **Measure the distance (D) between the rods.**
(Do this while the broiler is off!)
Example: D = 6 cm

2. **Multiply by 0.44.**
Example: 6 cm × 0.44 = 2.64 cm

3. **Add 5 mm.** The result is the ideal vertical distance from the bottom of the heating elements to the top of the food.
Example: 2.64 cm + 0.5 cm = 3.14 cm



Actual size

Food near the edges of a broiler's elements will cook unevenly if there are no side reflectors.

To use an electric broiler effectively, you thus must find its sweet zone. A simple approach is to use this rule of thumb: the center of the sweet zone, where the heat is most even, is about 5 mm / 0.2 in below the heating element plus just a bit less than half (44%) of the distance between the heating rods. If the rods are 10 cm / 4 in apart, for example, the sweet zone is centered 4.9 cm / 1⅞ in below the heating element.

If you want to make a broiler cook more evenly, then installing some shiny vertical reflectors near the edges will help a lot. Another good way to ensure that food browns evenly under a broiler is to wrap the dish with a reflective foil collar.

Food that is too close to the broiler element scorches directly underneath the rods, where the heat is most intense. Food that is too far also cooks unevenly because of shadows in the reflected infrared light being cast by the heating elements. But when the top of the food falls within the sweet zone, the radiant heat shines fairly evenly across its surface.

Too close

Uneven scorching is a telltale sign that the food was too close to the broiler elements.

Just right

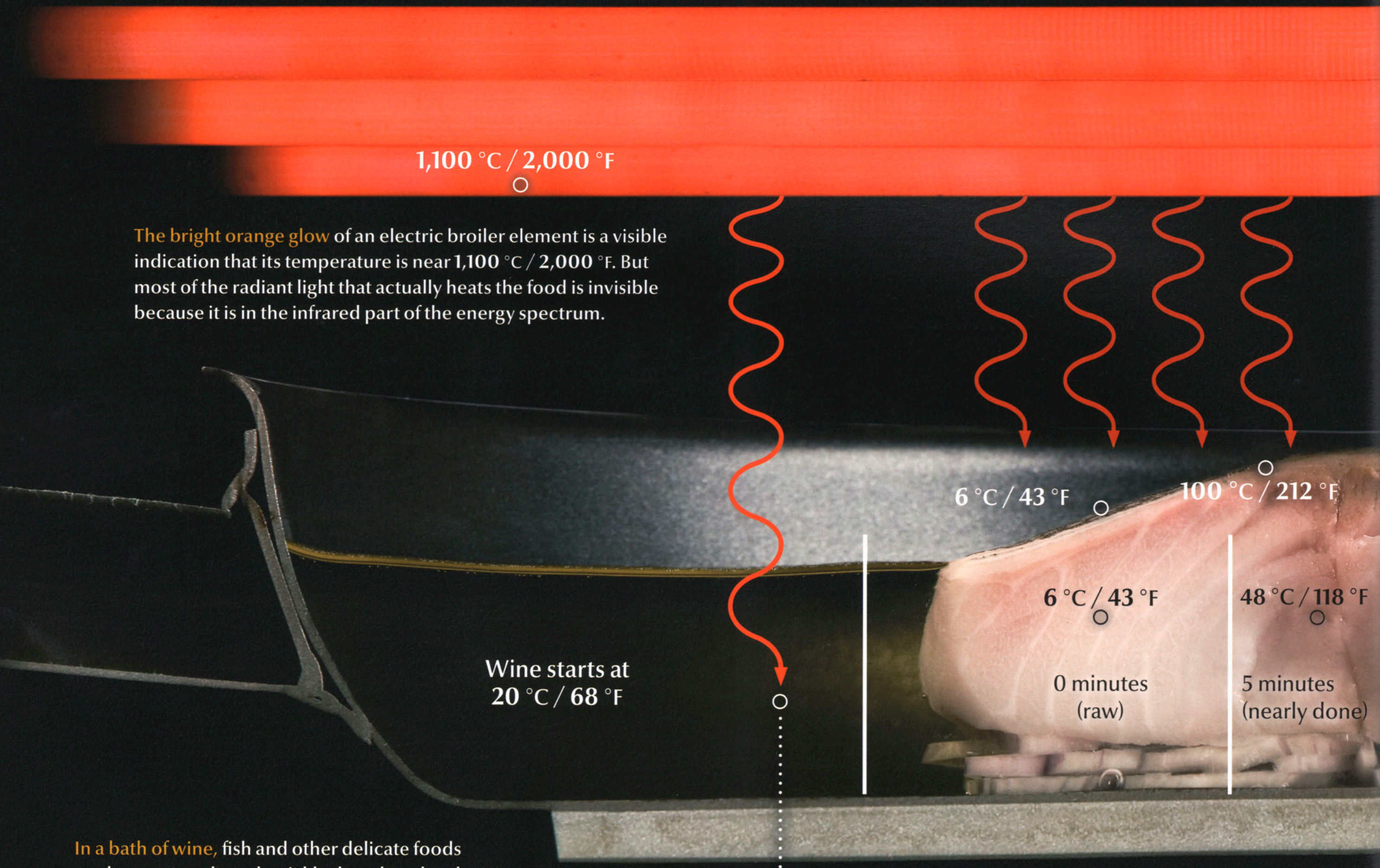
At the right distance, the heat beneath the rods and between the rods is nearly the same, so browning occurs evenly.

Too far

A splotchy surface, brown in some places and pale in others, results when the food is below the sweet zone of the broiler.

THE GIRARDET METHOD

An interesting broiling technique was devised, so far as we know, by the Swiss chef Frédy Girardet. He simultaneously poached and broiled delicate fish, and the result, like his cooking in general, was almost magical. The fish is all but submerged in a pan of cold white wine, with only the skin remaining dry. A bed of thinly sliced aromatic vegetables, such as the shallots shown here, holds the fish slightly above the bottom of the pan. Then the whole arrangement is broiled. The cooking goes slowly at first. But as the pan gets hot it warms the wine, which evenly cooks the fish through convection. Importantly, as the wine gets hotter, water and especially alcohol evaporate, cooling the wine. This is the truly clever aspect of this technique: vigorous evaporative cooling slows down how fast the wine gets hot. This effect keeps the bath of wine at moderate temperatures long enough to evenly poach a portion of fish through to the core. And, at just about the time the wine is getting too hot for cooking fish, the skin suddenly darkens to a crisp, golden brown.



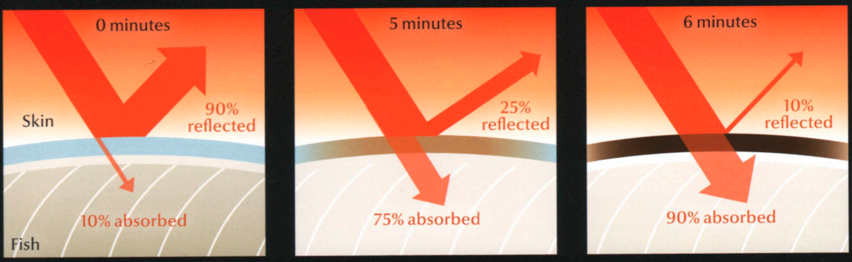
The bright orange glow of an electric broiler element is a visible indication that its temperature is near 1,100 °C / 2,000 °F. But most of the radiant light that actually heats the food is invisible because it is in the infrared part of the energy spectrum.

In a bath of wine, fish and other delicate foods cook more evenly and quickly than they do when they are broiled dry. Because wine evaporates so quickly, it stays cooler in the oven than water would. The liquid also helps to keep the fish succulent and moist as it cooks.

Wine is mostly transparent to infrared light, so the rays pass through the wine and heat the pan, which in turn warms the wine by conduction and convection.

Through a Mirror, Darkly

The mirrorlike shine of raw fish skin reflects much of the incoming heat radiation, so at first heating occurs slowly. But as the skin darkens, it reflects less energy and absorbs more, causing the temperature of the flesh to rise rapidly. That is why food under a broiler can burn in the blink of an eye.



A black pan absorbs most of the incoming radiation, so it heats up quickly—sometimes too quickly. A shiny pan, in contrast, reflects most of the infrared rays, so it heats more slowly.

Shallots under the fish insulate the fish from direct contact with the hot pan.

Like a tight-fitting lid, the wine prevents juices within the fish from evaporating. Not only does this keep the fish more succulent, but it also elevates the wet-bulb temperature, so the fish cooks faster. Wet-bulb temperature and its role in cooking are explained on page 1·319.

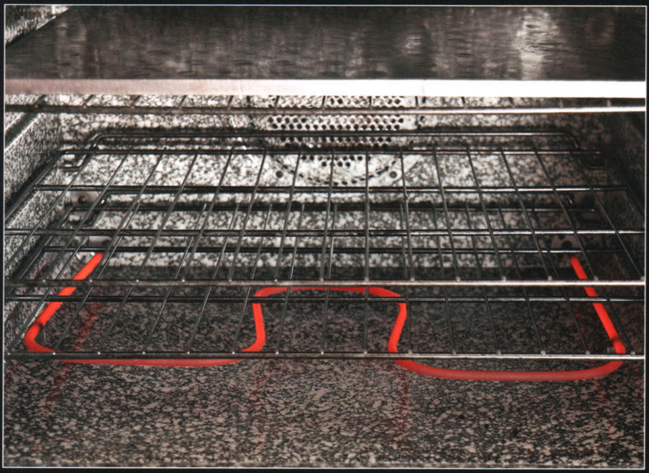
Boiling wine is a warning that the temperature is too high for cooking fish. Remove the fish before boiling begins, or the flesh will overcook.

HOW TO Make Your Electric Broiler Perform Like a Wood-Fired Oven

Italian pizza makers have a rule: Pizza Napoletana should take no more than two minutes to cook. Even slightly longer in the oven produces a crust that they deem too chewy. To cook the pie this fast requires temperatures near 425 °C / 800 °F, far above the upper limits of domestic and even professional ovens. Wood-fired pizza ovens can do the job because they are nearly perfect at radiating intense heat from above and have blisteringly hot stone beneath the pizza. Most homes lack a wood-fired oven, however. Fortunately, using only an electric broiler and a thick metal plate, you can cook a pizza that's as fast and as good as any you'll find in Naples.

1 Buy a metal plate (not shown). A piece of metal 2 cm / ¾ in thick and large enough to just fit in the oven is ideal—and surprisingly inexpensive. Either steel or aluminum works, but the latter is much easier to lift. An overturned iron skillet will do in a pinch. Because metal conducts heat better than the stone floor of a wood-fired oven does, you can get the same effect at a lower oven temperature.

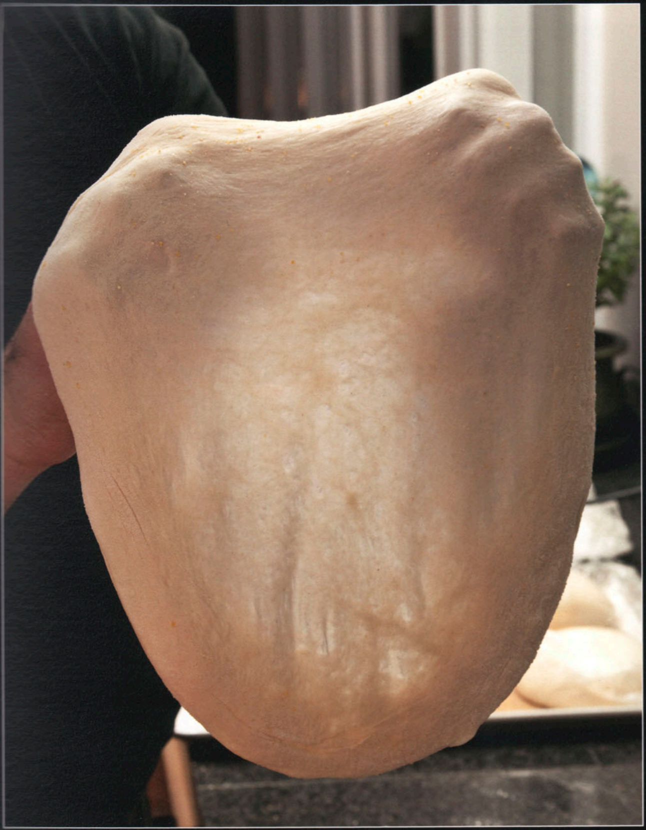
2 Put the plate in the sweet spot. Use the instructions on page 16 to calculate the ideal distance between the broiler elements and the pizza, and put the metal plate on an oven rack as close as possible to this sweet spot. (Usually this is the highest shelf position.)



3 Preheat the oven. Use the highest temperature available, which typically is 290 °C / 555 °F. Preheat for at least ½ h.

4 Turn on the broiler, and prepare the pie. Timing is crucial in this step and the next. Stretch out your dough, lay it on a peel, and place your toppings.

This technique was developed by Heston Blumenthal and Chris Young at The Fat Duck.



5 When the broiler is glowing, slide the pizza onto the metal plate. It's not necessary to close the oven door because the hot metal plate and glowing broiler do the cooking, not circulating hot air.

6 Bake for 1½–2 min. The heat from the broiler, at this close distance, generates more than enough radiant heat to mimic the intense glow of a wood-fired oven.

7 By the two-minute mark, the pizza should be done. Remove it from the oven. At about this same time, the broiler is usually overheating the oven, so the thermostat will shut off the element. You'll need to wait a few minutes for the oven to cool before you can make another pizza.

ROASTING

Just about everyone everywhere loves a great roast. The problem is that just about no one anywhere actually roasts food. Roasting has been nearly hyphenated out of existence, yielding to the pressures of economy and convenience to become pan-roasted or oven-roasted. These are admittedly more enticing adjectives than shallow-fried or oven-baked—both of which are important cooking techniques—but strictly speaking, neither actually roasts food.

True roasting cooks with radiant heat at a deliberately slow pace. When roasting, the food is held farther from the embers and flames of a fire than it is during grilling. The greater distance from the heat lowers the intensity of the radiation and thus the speed of cooking. But the extra distance also solves the dilemma of how to evenly cook large portions of meat and whole birds or other animals. Often the food rotates slowly but steadily as it roasts, so the heat varies, unlike the static heat that occurs during baking. The constant turning helps manage the pace at which heat accumulates in the food and assures even, consistent cooking.

To skillfully judge the best distance for roasting takes experience, but some guidance can be found in recipes from the 17th- and 18th-century royal courts of Europe. Spit jacks for large roasts were typically set up two to three feet in front of a great hearth. Only when the roast was fully cooked was it moved to within inches of the fire to brown.

A skilled roaster is able to balance the heat received with the heat absorbed. The trick, in other words, is to adjust the intensity of heat reaching the surface of the food so it matches the rate at which heat diffuses into the interior. Put the food too close to the fire or turn it too slowly, and heat will build up on the surface. That imbalance inevitably leads to a charred exterior and a raw center. Place food too far from the heat, and the opposite kind of imbalance occurs, so cooking takes much longer than it needs to.

Whether roasting the canonical chicken—a feast for a few—or a whole hog to feed a large gathering of friends, there are really only two significant decisions to make: how far from the fire should the cooking be done? And how quickly should the roast rotate?

Judging the right spot to roast from is tricky. A lot depends on the fire—is it a roaring outdoor bonfire or just an old-fashioned steady fire in a home hearth? If it's an indoor fire, then how well does the fireplace reflect radiant heat? The shape, depth, and wall material of the hearth all affect its ability to reflect heat.

The size of the food matters, too. Bigger roasts should be cooked farther from the fire and smaller ones closer, for two reasons. First, the time it takes for heat to penetrate to the center of a piece of food varies in proportion to the *square* of the food's thickness. So, all else being equal, a turkey that is 25 cm / 10 in across will take four times as long to roast as will a hen that is half that width.

As luck and physics have it, the intensity of heat from a blazing fire varies by the *inverse square* of the food's distance from the fire (with the proviso that the food must be several feet away from the fire for this relation to hold). That means that if the turkey is twice as far from the fire as the hen, the fire will deposit one-fourth as much heat on the surface of the larger bird as it will on the hen. If you keep these relations in mind, you'll find it easier to judge that perfect distance for roasting, where the speed of surface heating and the speed of heat penetration are balanced. Unfortunately, myriad other factors determine the ideal conditions for roasting, so this is more principle than formula. Experience helps a lot.

A lobster is an unconventional choice for the spit but in fact is ideally suited for roasting. The dark shell efficiently absorbs the intense radiant heat of the fire, quickly steaming the delicate flesh beneath the exoskeleton. The conventional approach of boiling the crustacean is easier but dilutes the natural sweetness of the flesh.

GOING WHOLE HOG

Roasting evolved in a bygone era, a time when most people owned livestock and slaughter was a familiar necessity. Because reliable refrigeration and freezing simply weren't available, people either cooked their animals immediately after slaughter or butchered them into smaller cuts for curing, drying, or smoking. Most often, they did both, preparing a small amount of the meat fresh, and preserving the majority for later.

This was also an era of village life and large families, and on festive days it was necessary to cook a whole animal so there was enough to go around. Roasting was, and still is, an ideal way to do this. Even animals of modest size, such as piglets and lambs, are too large for most ovens. But it's easy to build a fire large enough to slowly roast these animals to perfection. Doing so still takes some skill, and an experienced roaster pays attention to the details shown here.

Heat at the surface must pass, via slow conduction, through thick layers of solid meat to reach the center of the beast. Applying very intense heat to the surface won't speed cooking appreciably; it will simply overcook more of the roast's surface. Spit-roasting at a slow pace is the ideal way to cook the largest cuts of meat, even the whole hog.

On a rotating spit, each part of the pig sees the most intense heat arrive in regular pulses, which evenly brown and crisp the skin. In the meat beneath, the intensity of the heat averages out. As a result, most of the meat cooks to about the same degree, and only a relatively thin layer gets overcooked compared with the results you would get from baking.

Small, thin parts may overcook, particularly if they stick out closer to the fire. You can protect these with aluminum foil once they get done.

Scorch marks signal that part of the meat is too close to the fire. Cover the scorched areas with reflective foil to lower the heat there.

A large roast should be cooked far enough from the fire to be within the sweet spot of radiant heat (see page 16). At the right distance, the roast will cook through before the skin burns.

Consumed by flame, logs glow incandescently and emit the radiant heat that cooks the roast.

Heat varies as the inverse square of the distance from the radiant source only when roasting is done relatively far from the fire. As described in Grilling, page 7, and Broiling, page 18, this relation does not hold for those cooking techniques.

The second reason to cook bigger roasts farther from the fire is to ensure that the rays of heat fall evenly on the surface of the roast. The analogous situation in grilling is to position the food so it all falls within the sweet spot—that cooking zone where the intensity of the heat varies by less than 10% from one edge to the other (see page 14).

The width of the sweet spot for a fire of any size is shown graphically on page 16. The sweet spot is broad when the food is very close to the fire. Then it narrows in extent at awkward middling distances before broadening again farther from the fire.

The absolute numbers depend on the size of the fire, of course. But where the sweet spot is narrowest, it might be large enough to fit only a single chicken. A beef rib roast would cook unevenly at this medium distance because too much of the roast extends beyond the zone of even heating. Move the meat away from the fire just a little, however, and it will then cook evenly.

A tradeoff sometimes exists between the evenness of roasting and the speed. Where the food will roast fastest without burning often happens to be right where the sweet spot is narrowest. This coincidence is just unfortunate dumb luck. What to do?

One option is to build a bigger fire. A large enough conflagration will accommodate a roast of any size. A more pragmatic approach is to be patient. Move the roast away from the fire until the size of the sweet spot is sufficiently large. This approach extends the cooking time, but the roast will cook evenly.

If the food is now so far from the fire that the surface doesn't brown, move the roast close to the fire after it has cooked. Historically, this is exactly how the royal roast masters did things in Europe. They began cooking enormous beast-sized roasts far from a blazing fire, and then browned the meat close to the fire just before serving. Today, such skill is rare, but it can still be found in remote corners of the world unencumbered by a need for quick, convenient cooking.

To Turn or Not To Turn?

Roasting is often most effectively done on a spit. The spit may be horizontal or vertical; it may pierce the food, or the food may be tied onto the spit. But in all cases the spit makes it easy to evenly turn a roast in front of a fire. Spit-roasting, also called rotisserie, is so closely linked to roasting that it's often thought to be an essential feature, and sometimes it is. But other times it isn't.

Authentic Chinese Pekin duck is roasted without turning. The duck is hung from a stationary hook inside an oven that is fired to tempera-

Lamb roasted asado-style is a favorite traditional meal of the gauchos who herd cattle and sheep across the Patagonian grasslands in South America. Asado is one of the few examples of true slow cooking done by radiant heat.

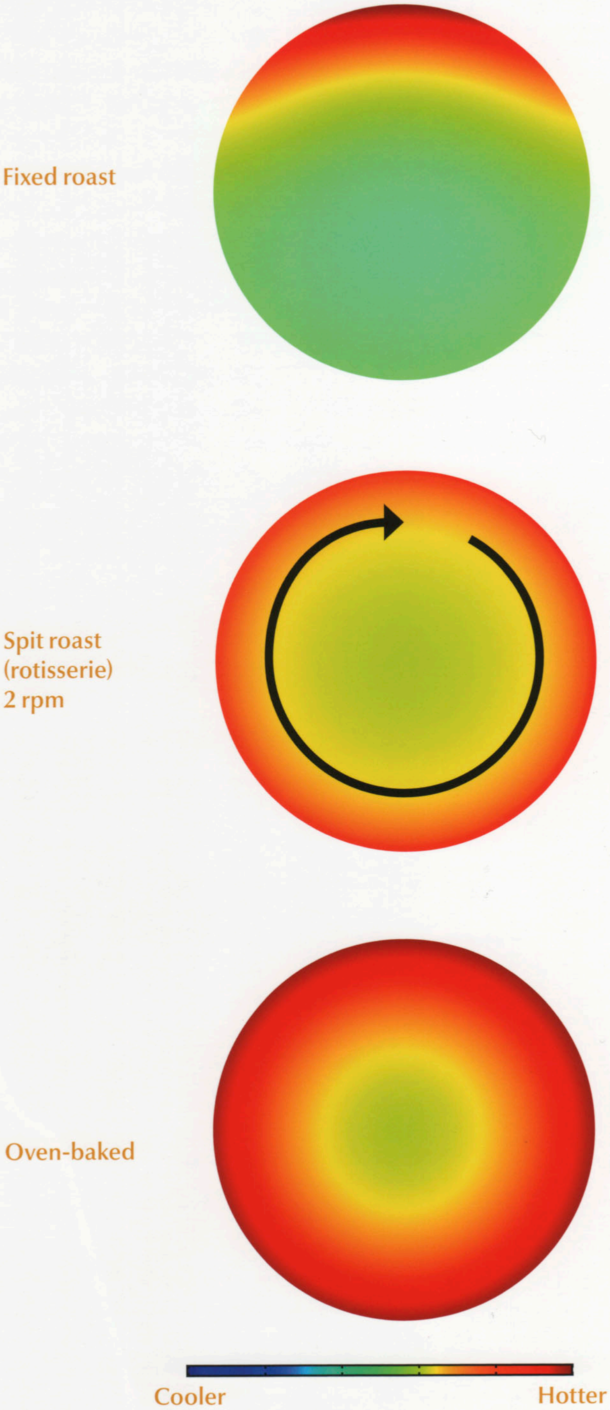
tures more akin to those in a potter's kiln than to those in domestic or even professional ovens. At a temperature near 450 °C / 840 °F, the brick walls and iron door of this specially-constructed oven emit an intense radiant heat that roasts the duck simultaneously from all sides.

The only Western ovens that work in a similar way are wood-fired pizza ovens; these roast rather than bake pizzas (see page 26). There are differences, of course, in the products of these ovens. Pizza, unlike duck, is flat and cooks quickly from both sides. And a great Peking Duck experience is all about the crispy lacquered skin rather than the flesh below, which too often is gray and overcooked.

To achieve both crispy skin *and* juicy flesh when roasting a Pekin duck, you have to forego the traditional oven and spin the food in front of a fire instead. The rotation effectively lowers the cooking temperature, but in a way different from simply lowering oven temperature or pulling the duck farther from the fire. Those actions lower both the peak and the average intensities. Turning a roast lowers the average intensity, but the peak heat remains high.

Alternating between heating and cooling is the secret to cooking a sublime roast. During each rotation, a given portion of the roast spends only a fraction of the time basking in a fire's glow; the remaining time is spent resting in the shadows, where it cools slowly. Some of the heat it absorbs while facing the fire convects and radiates away, and some of the heat slowly diffuses into the meat.

These two competing processes balance out such that the average heat flowing just below the surface of the roast is only a fraction of the peak heat at the surface. If everything is judged just right, the interior of a roast ends up, over a dizzying number of rotations, gently cooked to a shallow gradient of doneness from just below the surface all the way to the center, while the surface itself gets cooked to a crisp, deep-brown finish.



We used a computer model to simulate how heat flows within an idealized roast as it cooks when fixed facing a fire (top), on a rotating spit (center), or baked in an oven (bottom). The differences are startling. Radiant heat shines on only the fireward face of the fixed roast; the rest is shadowed from the heat.

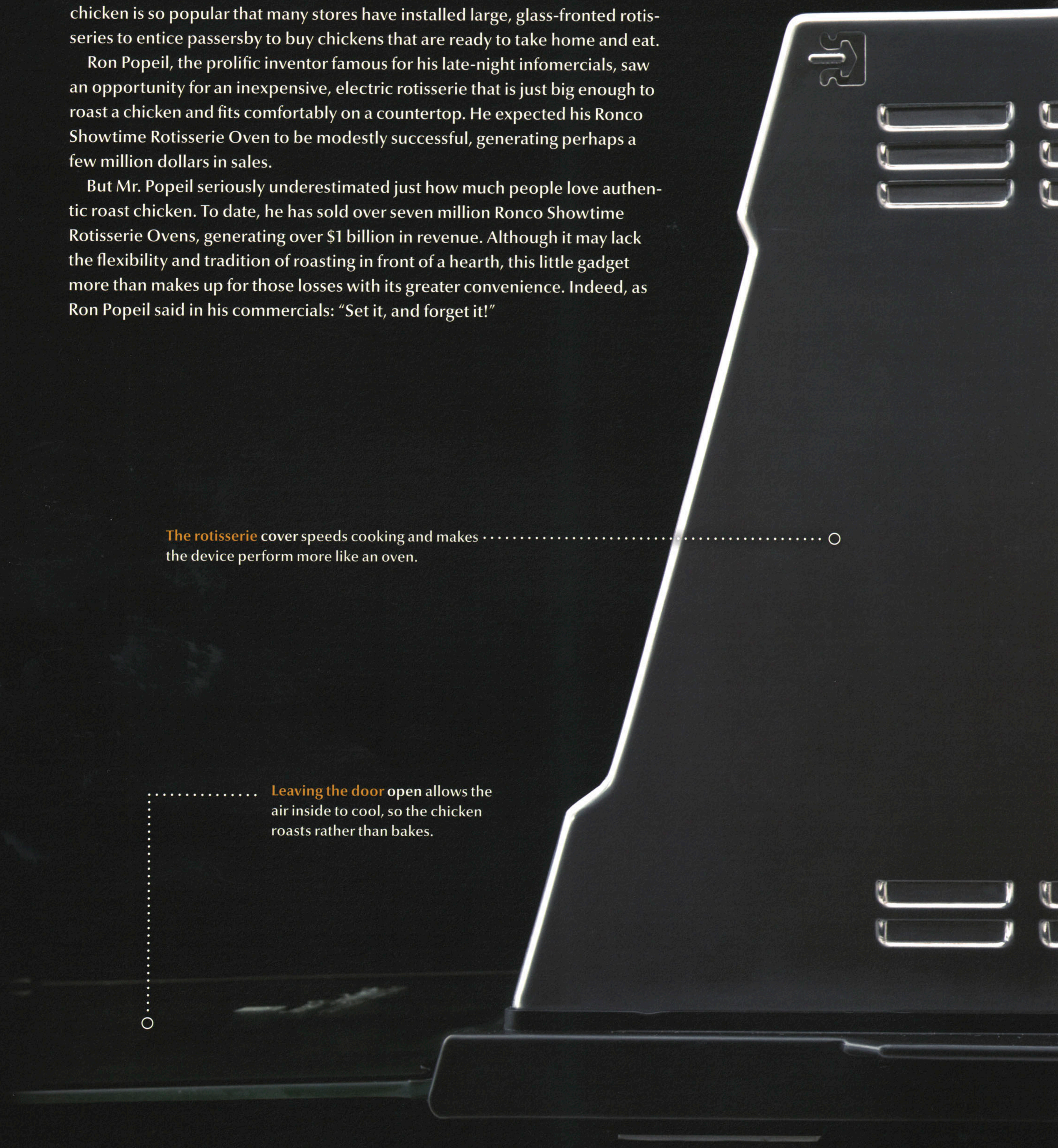
Turning the rotisserie spit gives equal cooking time—and cooling time—to all sides of the food. Oscillating between cooking and cooling moderates the flow of heat through the interior of the roast, cooking it very evenly while still searing the surface for a flavorful crust. In contrast, baking cooks all sides simultaneously (by convection rather than radiation), overcooking more of the meat than spit-roasting does.

BUT WAIT, THERE'S MORE...

Today, the only animal still commonly cooked whole is the chicken. Roast chicken is so popular that many stores have installed large, glass-fronted rotisseries to entice passersby to buy chickens that are ready to take home and eat.

Ron Popeil, the prolific inventor famous for his late-night infomercials, saw an opportunity for an inexpensive, electric rotisserie that is just big enough to roast a chicken and fits comfortably on a countertop. He expected his Ronco Showtime Rotisserie Oven to be modestly successful, generating perhaps a few million dollars in sales.

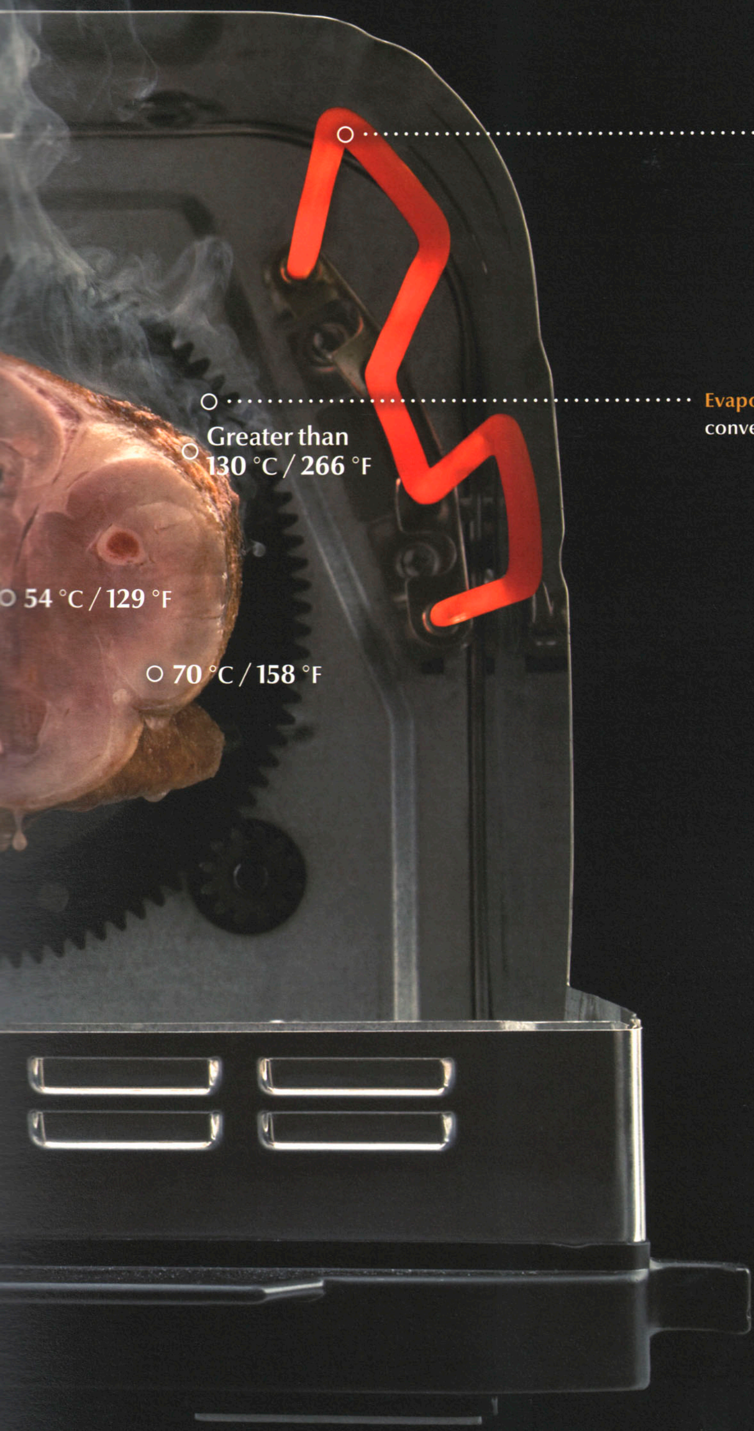
But Mr. Popeil seriously underestimated just how much people love authentic roast chicken. To date, he has sold over seven million Ronco Showtime Rotisserie Ovens, generating over $1 billion in revenue. Although it may lack the flexibility and tradition of roasting in front of a hearth, this little gadget more than makes up for those losses with its greater convenience. Indeed, as Ron Popeil said in his commercials: "Set it, and forget it!"



The rotisserie cover speeds cooking and makes the device perform more like an oven.

Leaving the door open allows the air inside to cool, so the chicken roasts rather than bakes.

The bird rotates at a fixed speed, which turns the skin away from the radiating element before it gets too hot. All else being equal, fast rotation overcooks less of the meat.



The larger the heating element, the more heat rays shine on the surface. More intense heat hastens cooking but results in a greater difference between the doneness of meat near the surface and of that at the core. Focusing heat more narrowly on the surface would cook the roast more evenly but less quickly.

Evaporating water, carried away by convection, cools the roast as it turns.

Many commercial rotisseries do not achieve the results of true roasting because they are enclosed, often by a glass door, which turns the rotisserie into an oven that partly roasts and partly bakes the food. It's faster to be sure—the high humidity trapped by the door helps speed cooking—but the average temperature is much higher. As a result, the roast often ends up overcooked just below the surface.

7

PANFRYING *A LA PLANCHA*

The daily existence of a short-order cook revolves around a never-ending battle for speed, very often waged in front of a griddle. Waves of orders come rolling in: eggs sunny side up, with bacon and a side of hash browns; cheeseburgers and grilled cheese sandwiches; pancakes and patty melts. The list is as long as the menu, and everything competes for space on the griddle. Speed is everything. A moment of hesitation or carelessness, and the cook will quickly be "in the shit."

But in the hands of a seasoned pro, a griddle—also known as a *plancha*—is unmatched for speed and versatility. If a food can be panfried, then usually it can be cooked on a griddle, too—and with fewer dirty pans to boot. You cannot change the temperature of a griddle on a whim, however, the way you can with a pan. So griddle cooking is more or less limited to one speed: fast!

The *plancha* pro starts with food that is flat and thin enough to cook quickly. For even cooking and no sticking, spread a thin layer of oil across the griddle to fill in the gaps between the food and the hot metal. Some fatty foods, like bacon, will render this oily coating on their own. Fluid foods such as pancake batter or raw egg flow across a griddle so smoothly that no oil is necessary.

The intense heat of the *plancha* will quickly polymerize oils and juices into a sticky film, which makes a mess and all but guarantees the food will stick. So it is important to regularly scrape away any grease or charred bits left behind on a hot griddle. Indeed, this need for constant scraping is the reason that nonstick coatings aren't applied to commercial griddles. The coatings wouldn't survive the abuse.

Foods that are a bit too large to be cooked quickly by the conductive heat of a griddle can be tamed with a simple trick: squirt a bit of water around the food on the griddle, then promptly cover it with a lid. The puddle of boiling water under the lid surrounds the food with steam, accelerating cooking.

Foods too large or thick for this trick, such as steak, need to be moved to an oven to finish cooking slowly. Alternatively, we can precook them and then finish them off with a quick sear on the *plancha*. Both of these approaches slow things down a bit and increase the complexity of finishing a dish. Consequently, short order-style restaurants usually avoid putting these kinds of dishes on their menus in the first place. In a battle, you do what you can to win.

A panfried egg on its way to perfection.
Does it matter what kind of pan it's in? No!
(See page 41.)

Flip Food Frequently

Whether cooking *a la plancha* or in a frying pan, people usually cook food on one side and then, about halfway through, flip it over to finish cooking it from the other side. The assumption is that this will cook the food more evenly from edge to edge. But is it the best approach?

No! A single flip cooks the food neither fastest nor most evenly. It just takes less thought. Food flipped twice will cook with greater uniformity; flip it four times for more even cooking still; and so on. Surprisingly, the more you flip, the faster the food cooks, too. Food science writer Harold McGee discovered these flipping effects, and we have verified them (see next page).

Uneven cooking happens whenever there is a gradient between the surface temperature of the food and the temperature at its core. The bigger the difference between these temperatures, the more uneven the cooking is. When food is cooked in a pan or on a griddle at 300 °C / 572 °F, the layers just below the surface of the food quickly reach the boiling point of water, even as the core remains much cooler. The temperature of the food surface rises the boiling point and stays there until the food dehydrates and browns. If you cook it for too long, the dry crust eventually burns.

Typically, the cook flips the food over before that can happen. Unfortunately, by that time, much of the food beneath the surface has been overcooked. Yet the core of the food is still undercooked. That's why you have to continue cooking the other side for nearly as long again.

While the flipped food cooks on its back side, the just-cooked surface temperature starts to cool down. Three mechanisms are at work simultaneously. First, some of the built-up heat at and near the surface diffuses through conduction toward the center of the food. Second, the hot water at the surface evaporates as steam. Finally, some of the built-up surface heat slowly convects away into the relatively cooler air of the kitchen. The total effect is to cool the cooked surface and heat the core.

Because the heat doesn't brake to an immediate stop but keeps on rolling toward the center, experienced cooks know to pull food from the griddle just before it's perfectly done. They then allow time for the residual heat to sink in, a process called **resting**. But how do you know exactly when to remove the food? Predicting how much the core temperature will rise during resting is difficult. Usually, cooks build up an intuition for the timing during years of trial and error.

Fortunately, there is an alternative approach that, although more laborious, is more likely to succeed for most cooks: frequent flipping. The more often you flip the food, the less time it spends against the griddle, and the less time the heat has to build up below the surface of the food. The result is that the overcooked layer is minimized, and more of the center is done just right.

In essence, constant flipping reduces the size of the swings that the surface temperature takes as the food surface alternates between cooking and cooling. It also lowers the *average* temperature of the surface, which means that, edge to edge, the food ends up more evenly cooked.

This effect shouldn't be too surprising. Most of us intuitively understand that rotating a roast on a spit helps cook the roast more evenly. Flipping food back and forth creates pulses of heat that produce very much the same result—both a golden crust *and* an evenly cooked interior.

Repeated flipping also speeds the cooking a bit because, in much the same way that it minimizes how much excessive heat builds up on the cooking side, it also reduces the amount of cooling that occurs on the resting side. Flip too frequently, however, and you'll get diminishing returns.

How often, then, should you flip? There is no single optimum, but somewhere in the range of once every 15–30 seconds seems reasonable.

Give it a try, and you'll discover the advantage of this unorthodox approach. Because the surface and core temperatures of the food never get very far apart, the interior temperature rises just a few degrees during resting. It thus becomes easier to estimate when to stop cooking, and timing things just right becomes less critical.

Day-to-day changes in the humidity of the kitchen are bigger than most people think—and they can wreak havoc on tried-and-true frying times. On a relatively dry day, resting food will cool more than you might expect because evaporation accelerates. The core temperature thus doesn't increase as much. Conversely, on a very humid day, evaporation slows and sucks less heat out of the resting food, and the final interior temperature ends up hotter than you might expect.

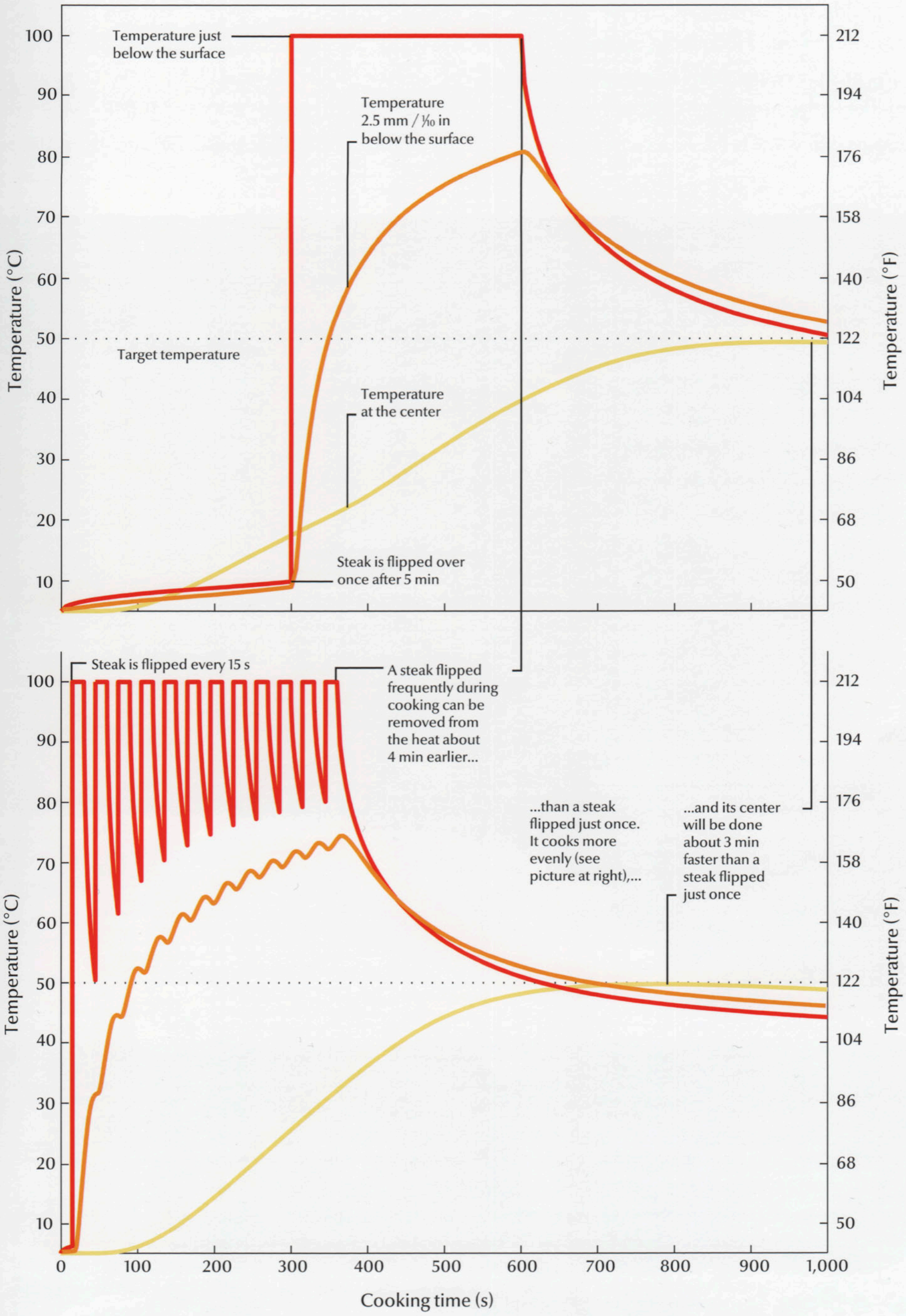
The solution is to tightly cover resting food with foil so that the humidity is consistently high—and predictable. For more details on how humidity affects cooking, see It's Not the Heat, It's the Humidity, page 102.

A pan loses heat constantly through radiation. This effect can be large for pans with dark surfaces, such as black cast iron, and is much smaller for shiny pans.

Flipping for Speed and Evenness

When a steak 2.5 cm / 1 in thick is flipped over halfway through cooking (top graph below), the temperature just beneath the surface of the food (red) rises rapidly and plateaus at the boiling point of water. As cooking progresses, the temperature a few millimeters further below the surface (orange) rises to about 80 °C / 175 °F, and a significant fraction of the steak overcooks. As the core temperature (yellow) nears 40 °C / 104 °F, the steak is removed from the heat and rested until the core temperature climbs to 50 °C / 122 °F.

By comparison, a steak flipped back and forth every 15 seconds (bottom graph) cooks faster and more evenly. The temperature a few millimeters beneath the surface peaks nearly 10 °C / 18 °F lower than that in a steak flipped only once, and less of the steak overcooks (bottom photo). The temperature at the core doesn't waver at all, and it rises faster than it does in the steak flipped once. You can thus stop cooking sooner– when the core temperature reaches 32 °C / 90 °F—and resting is complete minutes sooner, too.



Flipped once

Flipped every 15 seconds

What's in a Griddle?

A griddle might seem to be nothing more than a flat, heated plate of metal. That it is, of course. But look beneath the surface. How a griddle is heated has an enormous impact on how it performs.

Electric griddles tend to run a little hotter than those powered by gas, and it's easier to design them to heat evenly. Gas burners offer more raw power and so tend to be better at maintaining their temperature during heavy use. Both electric and gas griddles, however, have trouble handling large amounts of cold food placed on the griddle at once. The griddle responds by firing up the heat beneath the entire surface, not just warming the cooler spots below the food. As a consequence, annoying hot and cold spots quickly appear, making the griddle unpredictable and prone to burn food. To address this problem, larger griddles offer separate zones that are heated somewhat independently. These griddles are usually also made of thicker metal that stores enough heat to hold temperatures more constant.

But one company has developed a different and particularly interesting solution to this problem: it heats its griddle with water. AccuTemp builds a sealed, stainless-steel box that contains water and regularly spaced electric rods similar to those in an electric broiler. The rods heat the water to a temperature of roughly 200 °C / 400 °F—well above the usual boiling point. Because the water is

SEARING *A LA PLANCHA*

The duck breast presents a challenge to the cook looking for crispy skin and succulent meat. By the time the skin is crisped and the layer of fat underneath it rendered palatably thin, the tender flesh has been cooked dry and gray. The counterintuitive solution is to freeze the skin, fat, and a thin layer of adjacent flesh. The frozen water in the flesh slowly thaws while the skin crisps and the fat melts. The result is a duck breast with crispy skin and flesh that is pink and succulent from edge to edge.

Perforating the skin provides channels for oil liberated from ruptured cells to escape the tissue. Traditionally, this is why fatty meats like duck and pork belly are scored, but a large number of invisible pin pricks works as well without leaving scars in the crispy skin.

The frozen zone acts as an insulating layer, so the duck meat above it won't be cooked while you render the fatty tissue below it.

This unique Accu-Steam griddle superheats pressurized steam above the water to temperatures as high as **200** °C / **400** °F. At normal atmospheric pressure, water boils at **100** °C / **212** °F. To heat the griddle to temperatures suitable for frying, the steam needs to be pressurized to as much as 230 psi, a feat that requires strong, all-stainless-steel construction.

sealed inside a strong pressure chamber, however, it never boils. Instead, as pressure builds, high-temperature steam fills the space above the superheated water.

It's the steam—not a gas flame or an electric element—that directly heats the surface of the griddle. Because the steam remains at a consistent temperature, the surface of the griddle does, too. Even better, when cold food hits the griddle, the steam responds by condensing against only the cooled parts of the metal plate. The condensation releases a tremendous amount of latent heat (see page 1·314) just at that particular spot, rapidly restoring the griddle to an even temperature. It's a clever approach.

Skimp on the Pan, but Choose Your Burner Wisely

Expensive, gleaming copper pans are coveted by many people, even those who never cook. Hanging in a kitchen like trophies, they are gorgeous to look at. But do they really perform better than much cheaper aluminum or steel pans? Well, that depends on what you mean by "better."

Will a copper frying pan heat fast? Yes.

Will it respond quickly when you adjust the burner? Yes.

Will it diffuse heat evenly across its surface? Maybe; maybe not.

There is a lot of lore and pseudoscience surrounding what makes one piece of cookware

For more on how to cryosear using freezing to prevent overcooked meat, see page 3·124.

Wisps of smoke coming from the oil on the *plancha* indicate that the smoking point of the rendered fat has been reached. Compared with rendering by boiling or steaming, dry rendering tends to degrade the quality of the escaping oil, lowering its smoking point.

Pure duck fat typically melts at 14 °C / 57 °F, but much higher temperatures are needed to render the fat underneath duck skin. This is because, in fatty tissue, the globules of fat are trapped within individual cells that are in turn embedded in a matrix of connective tissue. The matrix breaks down and releases the oil only at temperatures near the boiling point of water—much higher than is ideal for succulent meat.

Steam condenses on the inner walls of the griddle because the cold duck meat above it has cooled the griddle surface. But the energy released by the condensation reheats the cold spot, returning that part of the griddle to the desired temperature.

Boiling water creates more steam when condensation lowers the pressure in the griddle chamber. When the pressure has been restored to equilibrium, the water will stop boiling.

better than another, but a rigorous analysis of the mathematics of heat transfer and material properties leads to some simple rules of thumb—and a few surprising conclusions.

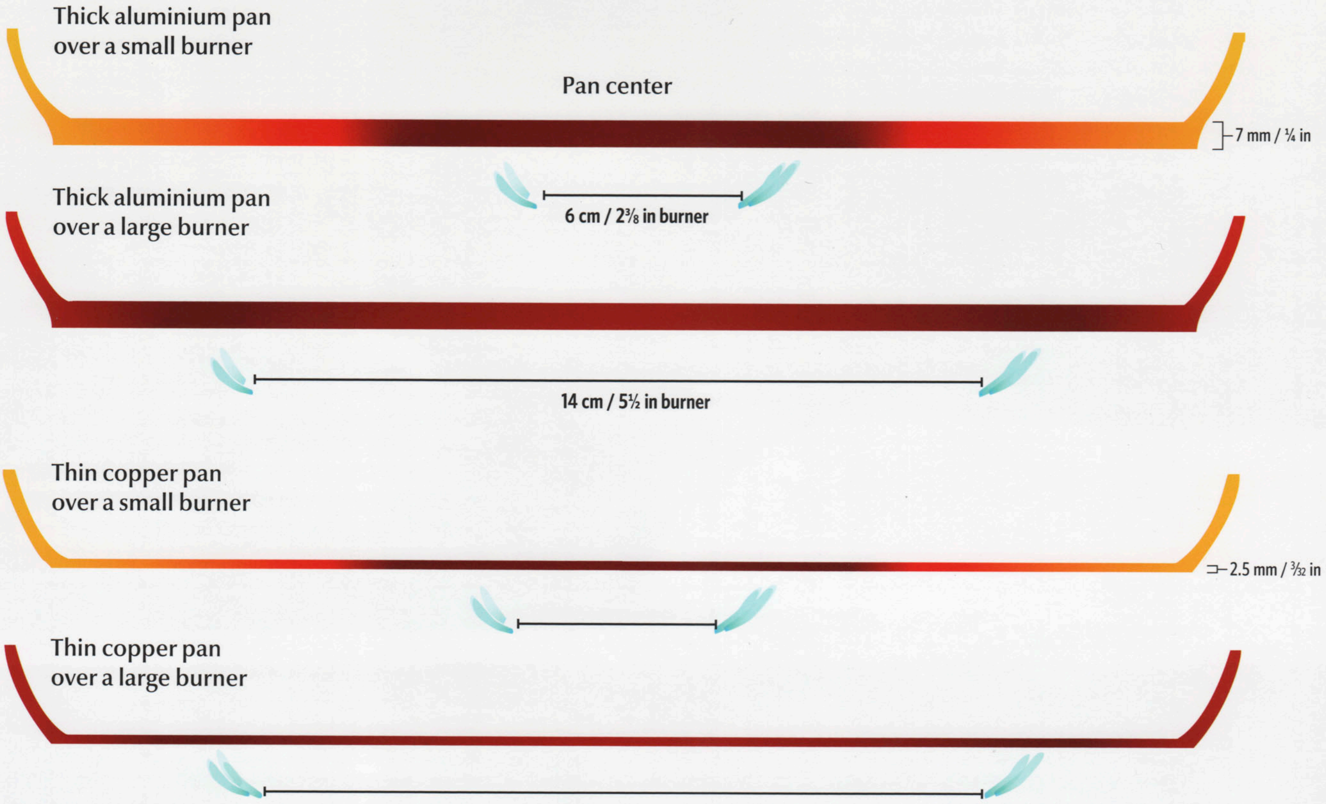
Let's start with the basics. All of the heat flowing upward from beneath a pan must go somewhere. At first, most of it goes to raising the temperature of the pan. As that occurs, conduction spreads the heat throughout the pan, from hot spots to cool spots.

You might think that eventually the temperature across the bottom of the pan would even out, but it doesn't. No pan can ever be heated to perfect evenness. That's because, while conduction is distributing heat throughout the pan, convection is carrying heat into the air above the pan.

As temperatures rise, conduction slows, whereas convection accelerates. Eventually the pan loses heat through convection faster than heat can spread across the pan. This competition between conduction and convection ultimately limits how hot a pan can get, as well as how even that heat is.

It's easy to understand why most people believe that pans made from copper and other metals that are good heat conductors will be highly responsive to burner temperature changes and will cook evenly. We're not saying high thermal conductivity doesn't matter at all. But it guarantees neither evenness nor thermal responsiveness. The thickness of the metal matters as much as or even more than the metal itself. Indeed, just how much it matters might surprise you.

The thicker a pan is, the bigger the conduit it offers for conduction to quickly move heat from one spot to another before convection at the surface can carry it away. Think of it as a freeway congested with traffic. If you want to get more cars (or heat) from A to B, raising the speed limit (or conductivity) a little will help. But adding a couple more lanes (a thicker base) will make a much bigger difference.



When it comes to even heating, the thickness of a pan matters more than the material from which a pan is made, and the size of the burner matters most of all. On a small burner, an aluminum pan (top) performs just as well as a thin copper one (second from bottom), and both outperform stainless steel—even if the steel pan is 70 mm / 2¾ in thick (right). A large burner produces even heat in all three kinds of pans, whether thick or thin, although the heat is not quite as even in a steel pan as in one made from copper or aluminum.

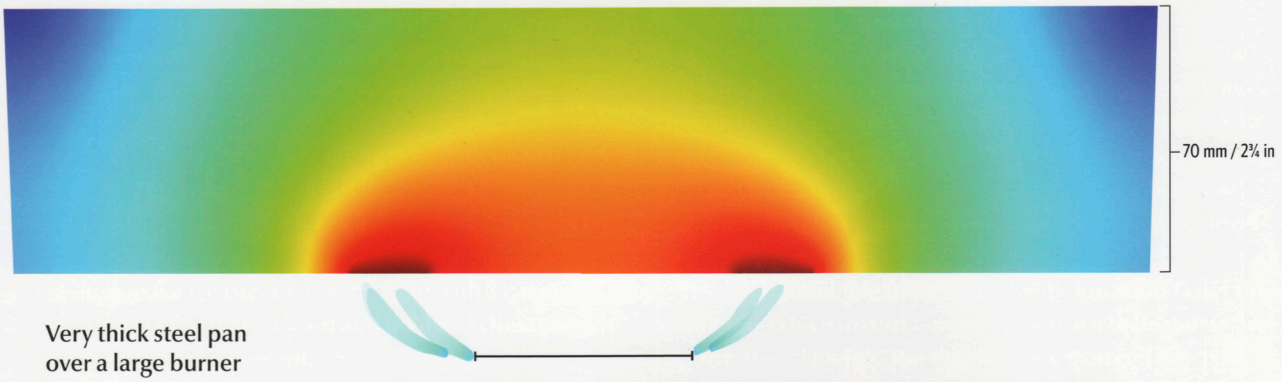
So as a pan gets thicker, it also distributes heat more efficiently, which results in a more uniform temperature across the surface. This isn't surprising. Most of us have noticed that thick, sturdy pans have fewer hot and cold spots. But this evenness comes at a price: the extra mass of metal makes a thicker pan less agile. It is slower to react than a thinner pan when the burner is turned up high or down low.

How thick is thick enough, then? The answer does depend on the conductivity of the metal. Take a typical copper pan, 25 cm / 10 in wide and 2.5 mm / ⅛ in thick, heated by a gas burner 14 cm / 5½ in. in diameter. The temperature across the bottom will vary by no more than 22 °C / 40 °F. But if the pan were made of stainless steel, then it would need to be more than 70 mm / 2¾ in thick to perform similarly—and never mind that the weight of such a pan would make it impossible to lift! Fortunately, bonding a lightweight, 7 mm / ¼ in plate of inexpensive aluminum to the bottom of the thinnest, cheapest stainless steel pan produces a pan with nearly the same performance as that of the copper pan (see illustrations below).

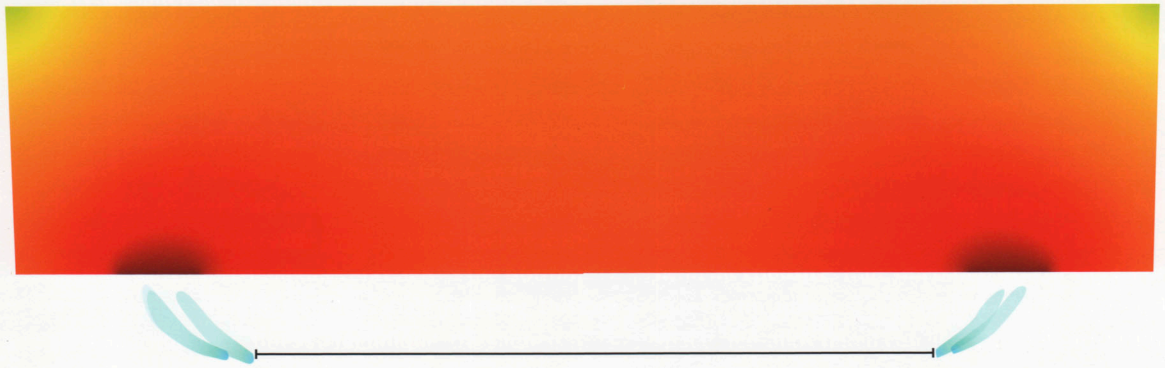
Now imagine that these same pans were heated instead by a small domestic gas burner only 6 cm / 2½ in. in diameter. Even copper isn't conductive enough to spread the heat evenly to the far edges of the pan. Any pan made from any material of any thickness will cook unevenly if the burner underneath it is too small.

What's the take-home message here? Whether the heat comes from the flames of a gas burner, the radiant glow of an electric coil or halogen element, or the oscillating magnetic field of an induction heater, the most important factor for ensuring that a pan heats evenly is burner size. With a properly sized burner—ideally about as wide as the pan itself—any pan, even a cheap and thin one, can be heated evenly.

Very thick steel pan
over a small burner



Very thick steel pan
over a large burner



SAUTÉING

To an experienced cook, nothing seems simpler than a quick sauté. Yet it is surprisingly difficult to do it well, especially amid the rush and impatience that too often prevail in professional kitchens. In such circumstance, a return to fundamentals can be helpful.

The overriding goal is to cook the food quickly. Cooking speed depends mainly on how fast you deliver heat to the surface of the food and how long it then takes the heat to flow all the way to the center of the pieces. Because heat almost always moves more slowly inside the food than at its surface, one rule of thumb is that smaller pieces are better. If you skip the small amount of extra effort needed to cut food into small pieces of uniform size, you are all but guaranteed a raw center, a charred surface, or both.

Oil is the second key to a great sauté. Use too little fat or oil, and you're risking undercooked food with burned bits. The reason is evident if you look closely at how food pieces rest in a pan. Even with relatively flat ingredients such as sliced mushrooms, only selected points on the edges and sides of the mushrooms touch the pan directly. Air gaps insulate most of the food from the hot surface. A generous layer of oil fills these gaps and conducts heat far more quickly from the pan to the food than air does.

Most cooks jerk the pan while sautéing to expose every face of the food pieces to the hot film of oil (see Flipping Good Flavor, page 46). Adding enough oil to match the amount and absorbency of the food you're sautéing is crucial. Otherwise, thin spots will develop in the film midway through the sauté, the food will start cooking unevenly, and some pieces may even stick to the pan. To avoid this problem, especially with meats, seafood, and other ingredients that tend to stick, mix oil with the cut-up pieces before beginning the sauté.

Not long into the cooking process, the food starts to release juices—mostly water. Water is the enemy of the perfect sauté. If the pan is overcrowded or the burner is too weak, the watery juices will accumulate and quickly depress the temperature to at most 100 °C / 212 °F. Food will not brown at such a low temperature, and the mouth-watering aromas from the Maillard reaction will not develop. Sautéing under such wet conditions really devolves into boiling or, worse yet, into stewing!

Allow plenty of free space in the pan, and use a burner with plenty of power. Most of the water released by the food will then evaporate in a flash as steam. Some of the water vapor will even condense back onto the surface of the food, releasing latent heat and improving heat transfer. As the surface of the food dehydrates, its temperature increases, browning begins, and enticing aromas rise from the pan.

If you listen carefully, the sounds coming from the pan tell you a lot about whether you're doing a good job. The sauté should start with a loud sizzle. That hiss is the sound of water rapidly boiling and escaping as steam. The sizzle also signals that you have good heat conduction between the pan and the food. If you don't hear anything, you have a problem: it means you're not cooking quickly enough. Perhaps the pan was too cold when you added the food, the pool of oil is too thin, the burner is too weak, or the pan is too crowded with food.

If all is going well, the sizzle is loud at first and gradually quiets as the surface of the food dries out. When that happens, pay attention to the aromas coming from the pan; they should be enticing. When the sauté starts to smell great, keep a close eye on it: the food will go from pleasantly brown to burned black with a mere moment's inattention.

THE TECHNOLOGY OF
Choosing a Sauté Pan

Contrary to what cooking-store marketers would have you believe, the *least* important component in sautéing is the pan itself. Only a few general features truly matter for making great sautéed food easily, and they are widely available in pans of modest cost.

Sauté pans are usually broad and shallow with slightly sloping sides. This shape maximizes the heat transfer between the burner and the pan; it also provides a large surface area where accumulating juices can quickly boil away. The sloping sides make it easier to toss the food with a circular motion that jerks the pan forward and then snatches it back while flipping the food upward.

Sauté pans generally are made of copper, aluminum, stainless steel, blue steel, or iron. They come in a wide range of thicknesses and myriad nonstick coatings. It seems that every option has it evangelist, and cookware manufacturers have made fortunes selling gleaming pans as lifestyle accessories. But does the kind of metal, the thickness, or the coating actually matter? Not really.

Certainly a thin the pan made from less conductive iron-based metals will diffuse heat unevenly across the bottom. For some cooking techniques, such as shallow-frying, this can be more than a nuisance. But as a technique, the sauté is tolerant of a pan with hot and cold spots because the food is moved around frequently, which essentially averages out these hot and cold spots.

What does matter, aside from a workable shape, is that you have a few pans in a variety of sizes so you can always choose one that is appropriate for the amount of food you want to sauté—large pans for lots of food, smaller pans for individual portions. Cover the surface of the pan evenly with food, and hot spots are then much less likely to develop and scorch the food.

Yes, it is undeniable that copper heats and cools faster than aluminum, which in turn is more responsive to heat than are the iron-based metals. But does it really matter if one pan responds twice as fast as another to an adjusted burner? Is this more nimble performance worth a few hundred dollars?

We don't think so. An expensive copper pan doesn't save you if your burner is underpowered for the amount of food you're trying to cook. And a cheap steel pan heats more than fast enough if your burner is up to the job. As proof, consider what happens when you use a wok to stir-fry, which arguably represents the ultimate form of sautéing. Woks are made from inexpensive, thin, uncoated iron or steel. Put one in a race for the quickest sear against a $400, high-tech-coated, space-age-alloy pan if you like. Our bets are firmly on the humble wok.

FLIPPING GOOD FLAVOR: MASTERING THE SAUTÉ

Experienced chefs sauté in a very hot pan and keep the food in motion. They know that the trick to a delicious sauté is cooking the food quickly and evenly. To do this well, use small pieces of food, a pan just big enough to contain the ingredients without letting them pile up, and a judicious amount of fat or oil. It's simple enough: cut up some mushrooms and perhaps some greens, toss them into a hot frying pan with a little oil—or, better yet, some sizzling butter—then give the pan an occasional jerk to keep everything jumping. Listen, smell, and look carefully to pick up the telltale sounds, aromas, and colors that signal the food is ready. Just add a pinch of salt and a dash of pepper to season; the result is delicious.

The tossing action exposes all sides of the food to the conductive heat of the pan and ensures fast, even cooking.

Leaking juices mix with the hot oil and explode into jets of steam that create the sizzling sound of the sauté.

A generous amount of oil or fat in the pan—even a nonstick pan—helps to transfer heat efficiently from the pan to the food.

Pan temperature:
175–230 °C / 350–450 °F

Food temperature at which browning starts to occur: approximately 130 °C / 265 °F

Moving the pan in a jerking, circular trajectory is a much more efficient way to control the heat than adjusting the burner power. This motion also keeps the pan from overheating, bastes the food in hot oil, and ensures that the cooking process remains under control. Use the larger muscles of the arm to avoid injuring your wrist.

The oil in the pan fills in gaps and wicks up the sides of the food, which helps distribute the heat evenly. With each toss, hot oil glazes the food and accelerates the cooking. If too little oil is used, even in a nonstick pan, the heat concentrates into the few points where the food directly contacts the pan. This process can cause parts of the food to scorch while other parts remain undercooked.

STIR-FRYING

For nearly 2,000 years, the wok has been the principal instrument of cooking in China. Originally cast as a thin, round shell of iron, the Cantonese-style wok is today more commonly forged from carbon steel, which is less brittle. Whether stamped into shape from the single blow of a machine or painstakingly hammered into shape by hand, a good wok is judged mainly by the quality of its patina. On both cast iron and forged carbon steel, the patina provides a protective barrier that inhibits rust from forming and food from sticking.

Traditionally, a wok is set over a very hot wood- or coal-fired stove, a practice still common in rural China. In the commercial kitchens of Beijing, Shanghai, and Hong Kong—or, for that matter, New York, London, Sydney, and everywhere else in the world that Chinese and Chinese-influenced cooking has taken hold—powerful gas-fired wok burners heat woks to temperatures more familiar to blacksmiths than to cooks.

Why such extreme cooking temperatures? It's all about achieving *wok hei* (pronounced "hay"), the almost indescribable flavor that is the defining quality of great wok cooking. Intense Maillard reactions on food surfaces combine with the partial breakdown of cooking oil at extremely high temperatures to produce this potent mélange of flavor compounds. The chemistry only works, however, if the burner has enough power to bring the surface of the wok to peak temperatures well above the boiling point of water.

Driving off the water (as steam) takes a tremendous amount of energy. Most of the foods we stir-fry release prodigious amounts of water as they begin to cook. The water quenches the heat of the wok, lowering the temperature to the boiling point until it has evaporated away. An underpowered burner will allow the juices to build up in the pan, and the food will stew rather than stir-fry. The resulting collection of aromas and tastes bears little resemblance to *wok hei*. This is the reason that domestic burners—or even Western-style professional burners—cannot reproduce the flavor of a true wok stir-fry. It's not the wok: it's the heat source.

For more on of the physics of boiling, steam, and condensation, see chapter 6 on The Physics of Food and Water, page 1·292.

Wok cooking involves intensely hot metal, searing oil, piping-hot steam, and shimmering waves of hot, dry air. Needless to say, this is a complex cooking environment. For simplicity's sake, let's divide it into three distinct cooking zones, which we'll call conduction, condensation, and convection (see Taming the Breath of a Wok, page 50).

In the conduction zone, on the surface of the wok, food cooks by direct contact with the oil-coated metal. This zone is by far the hottest of the three. Just above the surface of the wok lies the condensation zone, where the constant tossing action of the stir-fry keeps food cooking in a layer of steam. You can see wisps of fog in this zone as the steam condenses both in the air and also on the relatively cooler food, depositing significant amounts of energy as it changes back from vapor to liquid.

Well above the pan is the convection zone, a region of hot but dry air. Because air conducts heat poorly when it is devoid of water vapor, food cooks more slowly in this region. By lifting the food up off the wok and into the air, you can regulate the amount of time the food spends in each of the three heating zones. The true skill of the wok cook is thus a balancing act that manages the intense heat and speed of stir-fry cooking by keeping all of the ingredients in constant motion. The results can be delicious, but also a little dangerous: at these temperatures, most of the ingredients can become flammable, and a moment's hesitation could end in disaster and very possibly bodily harm!

Wok cooking is a balancing act in more ways than one. To achieve the authentic flavor of stir-fried dishes such as Pad Thai, one must master the intimidating heat of the wok with dexterity and unwavering focus.

TAMING THE BREATH OF A WOK

Stir-frying is one of the most dynamic of cooking techniques because you control the heat applied to the food primarily by tossing the ingredients. Using a constant circular motion that exploits the round shape of the wok, gather the food together and flip it up off the metal. Don't allow the food to spend much time in direct contact with the hottest part of the wok—the conduction zone—which can quickly scorch its surface. Lift the food pieces so that they spend most of their time cooking in the high-temperature steam in the conduction zone above the wok, with occasional forays into the drier, cooler air of the condensation zone.

The patina on the wok consists of black oxide, which prevents rust from forming on the metal, and a layer of decomposed fat, which bonds to the metal and yields a smooth, nonstick coating. Teflon and other modern nonstick coatings cannot replace the traditional patina and should never be used on a true wok. At temperatures greater than **260** °C / **500** °F, Teflon breaks down, and at temperatures greater than **340** °C / **645** °F, Teflon molecules decompose into toxic vapors.

Woks are usually made from either carbon steel or cast iron. The metal is relatively thin (~3 mm / 1/8 in) so that the pan is light enough to handle with ease. Although aluminum is commonly used to make Western cookware, it is unsuitable for woks because a professional wok burner gets hot enough to melt aluminum.

Hot air from the burner rushes past the wok and up into the kitchen hood. As a result, wok cooking is not very efficient. Much of the heat never makes it to the food. The inefficiency does yield one beneficial side effect, however: the rush of hot air helps carry smoke and steam away from the cook and into the hood.

Stir-fried food experiences a wide range of temperatures as it cycles repeatedly among three different cooking zones. Its average cooking temperature is a function of the time and total heat the food that experiences in all of the zones.

CONVECTION ZONE
The air well above the wok is somewhat cooler and contains less water vapor, so it transfers heat less efficiently. This region is still very hot, however, so food up here continues to cook, albeit much more slowly than when it is in the lower zones.

CONDENSATION ZONE
Food rising or falling through this middle region bathes in steam that is near **100** °C / **212** °F. The food itself is cooler than the boiling point of water, so some of the steam condenses onto its surface. The condensation deposits formidable amounts of latent energy that rapidly heat the food. It also forms a visible fog.

CONDUCTION ZONE
Food here cooks in heat conducted by direct contact with the pan, which diffuses the intense heat of the flame. At its hottest, the pan glows reddish-orange—an example of the phenomenon known as blackbody radiation (discussed in chapter 5 on Heat and Energy, page 1·260). Metallic atoms in the pan are transforming energy from heat to light. The color of the glow indicates the temperature of the metal, which can reach **760–815** °C / **1,400–1,500** °F.

The combustion of propane generates flames as hot as **1,980** °C / **3,600** °F.

Wok burners are unusually powerful, combusting far more propane or natural gas than other burners. The high power generates up to 25 times as much heat as a regular domestic gas burner can produce. The terrifically high temperatures that result create the unique taste of foods prepared in a wok—the *wok hei* or "breath of a wok."

THE TECHNOLOGY OF

Power to Burn

Running at full tilt, a wok burner can deliver up to 59,000 W (200,000 BTU/h) of thermal power. A burner of this capacity roars with a sound more akin to that of a jet engine than a stove top. By comparison, Western-style professional gas burners deliver 4,400–8,800 W (15,000–30,000 BTU/h), and domestic gas burners burn with a comparatively anemic 1,750–4,100 W (6,000–14,000 BTU/h). High-powered wok burners are capable of raising the temperature of a wok to almost 1,200 °C / 2,200 °F, a temperature well beyond that encountered in Western-style cooking. Heat this high softens steel rapidly and causes the wok to warp with use. In a busy professional kitchen, a wok may need to be reforged into shape every few days and replaced every few weeks!

The awesome power of wok burners can quickly get out of hand.

HOW TO Season a Wok or Frying Pan

A newly forged wok is susceptible to rust and to sticking food until it has acquired a proper patina. Cantonese chefs accomplish this by *hoi wok* or "opening the wok." Myriad rituals surround this process, but only two steps are truly crucial: first you must oxidize iron into the black oxide known as magnetite (Fe_3O_4), instead of the more common red oxide hematite (Fe_2O_3), also known as rust. The second step is to form a durable, waterproof film made from oxidized fat that is bound electrochemically to the metal.

You accomplish both steps by coating the wok with animal fats or vegetable oils, then heating it to very high temperatures, typically more than 480 °C / 900 °F. This is the same process that is used to "season" a new steel or cast-iron frying pan in Western-style cooking. At these temperatures, the fats decompose into an assortment of molecules, including fatty acids and a class of chemicals known as esters. The acids provide the caustic conditions necessary for high temperatures to oxidize iron into magnetite. The esters form a strong and durable film bound to the metal that repels water and protects the wok from the food. With proper use and care, the patina becomes thicker and more durable over time. It's the patina that makes a wok or a skillet nonstick.

1 **Why season?** The raw steel of a new wok will quickly rust and food will stick and burn until the wok has been seasoned.

2 **Rub on oil or fat.** Work a thick layer of vegetable oil or rendered animal fat into the wok surface while it is cold.

3 **Heat the wok.** Raise the temperature of the oiled wok above the smoke point and maintain the heat to crack the oil. New kinds of molecules will form, oxidize the iron, then polymerize into a waterproof film bound to the metal.

4 **Check the patina.** When the smoke has abated, verify that the wok now has a shiny patina. To keep the wok rustproof and nonstick, repeat the seasoning when the shine begins to fade.

The Basic Techniques: *Bao* and *Chao*

Meat and seafood cooked in a wok is often coated with a cornstarch gel before cooking, a process known as "velveting" that is discussed in chapter 14 on Gels, page 4·64.

In China, wok cooking involves two fundamental techniques, known as *bao* and *chao*. The *bao* technique is the true stir-fry. The wok must be hot enough that it glows a dull red color. Only then does the cook add oil (usually a generous amount), seasonings, and meats, in very rapid succession. There is no room for hesitation; oil combusts, and food burns, almost instantly at temperatures this high. Water in the food evaporates in a flash into steam, so juices do not leach out, accumulate in the bottom of the wok, and "stew" the food, as can happen in sautéing. Food browns very rapidly in wok cooking, and the rapid browning generates more of the flavorful compounds that result from Maillard reactions, more of the partially combusted cooking oil, and thus more of the characteristic *wok hei* flavors.

An expert at *bao* cooking keeps control by continually tossing the food in a circular motion, stopping for at most a few seconds to add vegetables or broth. With each rhythmic beat, the cook gathers the food together and flings it into the steam-filled air above the wok, which is cool in comparison with the metal glowing incandescently below.

Using food cut to the right size is crucial to success with the *bao* technique because the temperature gradients are so steep. Pieces must be small enough to cook all the way through before the outside of the food burns. Small pieces are also easier to gather and flip. Wok cooks using the *bao* technique exploit the curved shape of the wok by tilting it on the burner so that less of the wok is heated. The food comes into direct contact only with the cooler metal on the far side of the wok.

The *chao* technique is more akin to the Western technique of the covered sauté, which is described on page 58. To cook using the *chao* approach, heat the wok to a moderate temperature (not as hot as in the *bao* technique), then add cooking oil. Dry ingredients, typically garlic and ginger, come next. Meats, if called for, are then added and quickly seared. Vegetables and any liquids go into the wok last.

Usually you cover the wok to let the liquids finish cooking the other ingredients by a combination of boiling and steaming. Because the *chao* technique does not require the staggeringly intense heat used in *bao* cooking, it is a good approach when using a burner of modest power. It is also an easier technique to master, whereas *bao* cooking demands the speed and agility that come only with years of practice and a healthy fear of the fire's bite.

The patina of a wok—as well as the generous use of cooking oil—provide the nonstick qualities that make the bao technique possible.

LIFT OFF!

The crux of the *bao* technique is to control the heat by cooking both in the wok and also in the air above it. The arm motion you use to tame the heat depends on the style of wok you use. A Northern-style Chinese wok is small and light and has a long handle that makes it relatively easy to snap the wok forward, then jerk it back to keep the food jumping—a muscular action identical to that of the Western sauté.

A Cantonese wok has no handle and typically is so large and heavy that a handle would be of no use anyway. So rather than moving the wok, you use a ladle or spatula-like utensil to move the food, drawing it together and then flinging it into the air off the curved backside of the wok. If all goes well, the food falls back into the wok. But this last step requires practice.

3 **At the last moment, jerk the wok back slightly, which bounces the food in a looping trajectory that ends back in the wok.**

2 **Quickly push the food up the far side of the wok, which is cooler than the bottom.**

1 **Use a ladle or spatula-like tool to gather the food together at the hot bottom of the wok.**

MAKING *CHAO* CHOW

For small, quick-cooking foods, the speed of the *bao* technique is unbeatable. It doesn't work well with chunkier foods, however, because the intense heat from the wok can't reach the core before the surface of the food burns. A better approach with large pieces of food is to quench the intense heat of the wok with water, which reduces the temperature difference between the surface and the center of the food.

The Chinese *chao* technique does just that. A combination of boiling juices and steam vapor, trapped by a lid covering the wok, insulate the outside of the food from the burning heat of the wok long enough for the inside to cook through.

1 **Quickly stir-fry aromatics such as garlic and ginger in oil.**

2 **Add vegetables to the aromatic, shimmering-hot oil.** This quickly quenches the heat of the wok.

Rapidly boiling juices: **100** °C / **212** °F

A high-power wok burner ensures that the vegetables steam, rather than stew, in their own juices.

3 **Cover the wok with a lid.** The vegetables will quickly wilt from the heat, releasing natural juices that flash to steam, then condense to cook the vegetables through.

Condensing steam vapor:
100 °C / **212** °F

COVERED SAUTÉING

In the previous section on Stir-frying, we discussed the Eastern *chao* technique for cooking large or very wet foods. The counterpart to this technique in Western cooking is often called a covered sauté. The technique works well for ingredients so big that the intense heat of an uncovered sauté pan would scorch their surface before the interior cooks through.

There is more to a covered sauté than simply putting a lid on the pan. Often you first sear the food in a generous amount of hot oil. This approach works best for meats and seafood whose surface can be quickly seared before a torrent of juices floods the pan. Wait for the food to finish searing and for juices to begin accumulating before covering the pan with a tight-fitting lid.

The simple addition of a lid changes the cooking process in surprisingly complex ways. High-heat sautéing is transformed into a gentler, lower-temperature combination of boiling and steaming. The boiling juices lower the temperature at the surface of the pan to 100° C / 212° F, thus preventing the food from scorching (but also preventing it from browning). Nevertheless, it is still important to give the covered pan periodic jerks that move the food around and keep it cooking evenly. When cooking very dry foods, add water or some other flavorful liquid to moderate the heat and finish the cooking.

Many varieties of vegetables are nearly impossible to sear because their juices leak out so fast. In such cases, there's much less benefit from quickly searing the surface anyway. Unlike protein-rich foods like meat and seafood, vegetables tend to lack the chemical components that make the Maillard reaction work. Vegetables do contain plenty of natural sugars that will caramelize, but it doesn't matter whether this process happens at the beginning or the end of cooking.

We thus often apply a variation to the covered sauté, called glazing, to many plant foods. As far as we know, glazing is a uniquely Western cooking technique. You usually begin by adding the food to a cold, rather deep pan along with some butter or other fat. You then cover the pan tightly and put it over moderate heat. The butter soon melts and covers the bottom of the pan, aiding efficient conduction of heat from the pan to the food.

Unless the ingredients are very dry, add no water (beyond the trivial amount in the butter) because that would dilute the juices sweating out of the warming vegetables. As the juices begin to boil and steam, the vegetables cook in their own essence. Again, be sure to jerk the pan every so often to mix the food and even out the cooking.

Traditionally, the final step is to make a sauce from the drippings. Once the vegetables have cooked nearly through, remove the lid, strain out the vegetables, and allow the juices to boil down and concentrate the natural sugars they contain. The turbulence of the boil emulsifies juices with the butterfat or oil to form a rich, sweet glaze that can be used to coat the vegetables. Although glazed vegetables, being more caloric, are more fattening to eat than are steamed or boiled veggies, the glazed variety are certainly tastier.

Fernand Point, the father of modern French cuisine, famously said "Beurre, beurre, donnez-moi du beurre, toujours de beurre!" For glazing vegetables, we can only agree: butter, give us butter, always butter!

7

COOKING VEGETABLES IN THEIR OWN SWEAT

There are two distinct ways to perform covered sauté. The first, which is well suited to larger pieces of food, combines sautéing with boiling and steaming—much like the *chao* method of wok cooking discussed on page 56. Here we see an example of the second approach, called glazing, which dispenses entirely with sautéing. Glazing instead combines the speed of boiling with the flavor-preserving benefits of steaming and the richness of butter or oil.

Shaking the pot regularly mixes the vegetables, thus ensuring even cooking and glazing them in the butter-enriched juices.

At **10** °C / **50** °F, the cores of the thicker vegetables are just starting to warm.

Condensing steam quickly raises the surface temperature of the vegetables above **92** °C / **198** °F, hot enough to soften plant tissue and let the juices leak out. Free-flowing juices within the tissue accelerate cooking, which is why vegetables can go from nearly done to overdone so quickly.

Naturally sweet vegetable juices accumulate in the covered pot. Simmering at **95–100** °C / **203–212** °F, the juices cook the vegetables in their own sweat.

At **28** °C / **82** °F, the butter is just starting to melt.

The butter has completely melted at **36** °C / **97** °F. The narrow melting range just below human body temperature gives butter its melt-in-the-mouth quality.

Juices from the vegetables combine with the melted butter to form a simple sauce. Add a small amount of starch to the butter before cooking to make a thicker sauce.

BOILING

Although somewhat ill-defined as a culinary term, *à l'Anglaise* translates loosely as "cooked in the English manner." Francophiles tend to fling the term as a barb to suggest the manner in which they believe the English would cook something: boiled to death, insipid, and with no sauce. Ridiculed though it may be, boiling is a classic method for cooking food quickly.

The very simplicity of boiling a pot of water makes it a useful cooking strategy for many foods, especially vegetables. Take the classic French dish *haricot vert à l'Anglaise,* a.k.a. boiled green beans. The instant the beans plunge into boiling, salted water, their color changes from dark green to a bright, intense, and quite appetizing spring green. Cooks typically describe this effect as "fixing" the color, but fixing the color doesn't make vegetables any less raw (see page 66). Delicate vegetables such as green beans may be pleasantly crunchy and still raw after a quick blanching, whereas larger vegetables need to boil a bit longer in order to soften their tissue while still leaving just enough firmness for a toothsome bite.

Cookbooks often insist that when boiling food you should never let the pot of water come off the boil. To the scientifically minded, that advice might seem dubious at first glance. How could blanching in water a degree or two cooler than the boiling point possibly make a difference? After all, heat transfer is proportional to the difference in temperature between the food and the heat source, so a couple of degrees shouldn't make much of a difference—yet experience shows that it clearly does.

Boiling water may be only slight hotter than near-boiling water, but it is far more turbulent. Because boiling water moves chaotically, it conducts heat into the surface of the food two to three times as fast as stagnant water a few degrees cooler does. If that seems counterintuitive, think about what you do when you get into a really hot bath. You try to stay as still as possible because stirring the water makes it unbearably hot. The overall temperature of the water is nearly the same in either case, but flowing water feels much hotter because it hasn't had time to cool off against your skin. The greater rate at which boiling water transfers heat makes it worth the extra effort in many cases to blanch food in small batches and in a big pot so that the water maintains its roiling boil. The food will cook faster and will retain more of its flavor, color, and nutrients.

Boiling cushions food in water and maintains a constant, relatively low temperature, so it may seem to be a gentler way to cook food than roasting, frying, or baking. The boiling point of water is actually far hotter than necessary or ideal for meats, seafood, or even eggs, however. Moreover, water transmits heat so much more efficiently than air that it raises the food temperature extremely rapidly, which makes it tricky to time the cooking perfectly. Boil a chicken breast or fish fillet for a few dozen seconds too long, and it overcooks. A perfect boiled egg is hard to achieve even with a stopwatch.

The proteins in eggs, meats, and seafood are much more delicate than tough plant tissue. They are at their most succulent and tender when poached at temperatures far below the boiling point, at which heat transfer is slower, the temperature gradient within the food shallower, and the margin of error for perfect doneness wider.

A high-tech approach to cooking meats, seafood, and even the proverbial "boiled" egg at low temperatures is to use a digitally controlled water bath, which can achieve unrivalled accuracy and precision, as is described in chapter 9 on Cooking Sous Vide, chapter 11 on Meats and Seafood, and chapter 14 on Gels.

The boiled egg: simple to boil, difficult to perfect.

BOILING *À L'ANGLAISE*

A classic method for cooking food quickly, boiling owes its speed to the outstanding ability of water in motion to conduct heat. The "in motion" part is crucial, at least for small pieces of food. Simmering water cooks relatively slowly, but a rolling boil cooks fast because the turbulence lifts the hottest water up to the surface, drags colder water down toward the bottom of the pot, and accelerates the transfer of heat. The large breaking bubbles of a rapid boil also conveniently signal that the water is hot enough for cooking.

Heat is lost as water on the surface evaporates into vapor.

Bubbles are filled with steam, which is hotter than the boiling point of water.

Evaporation cools the water slightly. Covering the pot slows evaporation, reduces heat loss, and brings the water to a boil faster.

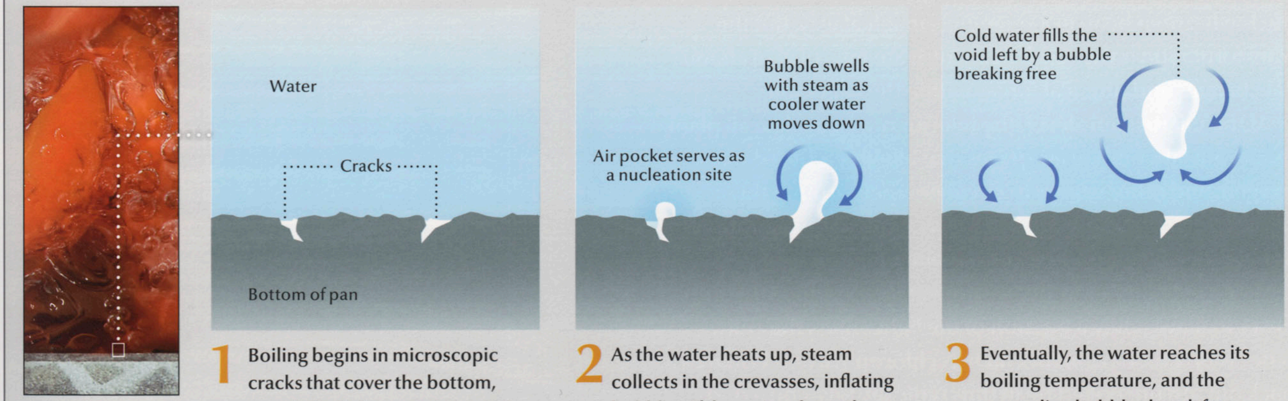
Hot water seeping into the vegetable dissolves the molecular glues (hemicellulose and pectin) that hold plant tissue together, and weakens the cell walls that give it rigidity. The carrots then change from raw and crunchy to cooked and tender. Slightly salty or alkaline water cooks the carrots faster than hard or slightly acidic water does. Because of that effect, you can speed up the cooking by adding a few spoonfuls of salt to the pot. Slow the cooking by adding a slug of vinegar.

Water also dissolves the sugars that make vegetables naturally sweet. This result accounts for why boiling makes a carrot bland: much of the sugar content of the carrot ends up in the water. Steaming or sautéing carrots with butter in a covered pan spares their natural sweetness.

The Birth of a Bubble

Even the largest of bubbles in a roiling pot of water has humble origins. It starts small, in a fissure or at some other especially rough point.

Steam inflates the bubble like a balloon until its buoyancy overcomes the resistance of the surrounding fluid, and at last it achieves lift-off.



1 Boiling begins in microscopic cracks that cover the bottom, even in brand new pots. Liquid water has such high surface tension that it is unable to fill these grooves and pits.

2 As the water heats up, steam collects in the crevasses, inflating bubbles. If the water above the bubbles is too cold, the steam condenses, and the bubbles pop.

3 Eventually, the water reaches its boiling temperature, and the expanding bubbles break free, drawing cooler water into the spots left behind and allowing the cycle to repeat.

A rolling boil cooks small pieces of food faster than a simmer because the churning water creates turbulent convection, which doubles or triples the speed of heat transfer. In a simmering pot, cooler stagnant water covers the carrots and slows their cooking. This characteristic is less important for larger pieces of food, for which the limiting factor is how fast heat can move within the food via conduction.

Convective currents mix hot and cold spots quickly and leave the bulk of the water exactly at its boiling point.

A crowded pot traps water into stagnant pockets and creates cool spots.

Water superheats along the bottom to **102–108** °C / **216–226** °F when the pot is at a full boil.

THE CHEMISTRY OF

"Fixing" Color

Just a five-second plunge into boiling water alters the look of the lowly green bean in a seemingly magical way. But the transformation is the result of an intricate interplay of chemical changes and physical forces within the vegetable.

At the microscopic level, the interior of a bean, like all plant tissue, is a labyrinth of air spaces that allows carbon dioxide, oxygen, and other vapors to circulate freely around the plant's cells. That circulatory process is called transpiration, and it is crucial for photosynthesis and plant survival.

When light hits a raw bean, some of it enters the labyrinth, never to leave. Only a fraction of the light enters the cells, reflects off green pigments such as chlorophyll and bounces back out. An uncooked bean thus typically takes on a dark, somewhat muddy shade of green.

As boiling water rapidly heats the surface of the bean, however, it bursts the walls of the labyrinth, which then collapses and fill with water. Now more light reflects directly off the color pigments and back out to the air, so the blanched bean shines with a brighter, more vivid color. Similar, although less pronounced, changes happen to fruits and vegetables of other colors, too.

Complex natural forces transform the color of snap beans from a deep olive to a bright spring green with just a couple of seconds of blanching. This photo shows a gradient of color from drab-green, raw beans (at the top) to bright-green, blanched beans (at the bottom). The gradual change can be hard to perceive if you look at a small section, but if you put your hand over the center of the image, you can easily see that the beans at the top are different in color from those at the bottom.

THE PHYSICS OF

Why We Stir the Pot Before Poaching an Egg

To make a decent poached egg it is important to stir the boiling water in the pot so that it is swirling rapidly, then crack the egg and drop it in. The white and yolk will nicely collect themselves into a single mass at the center of the pot. If you don't stir, the egg white will tend to spread out all over the place.

Many cooks know this trick, but not many of them understand why it works. The phenomenon at play here, called Ekman pumping, also accounts for why, in the days before tea bags, the bits of tea leaves that sank to the bottom of the cup would collect at the center when you stirred.

When you stir the pot, centrifugal force flings the water molecules outward, as if they were kids on a schoolyard merry-go-round. Water thus piles up around the outside and gives the surface a convex shape.

As any diver knows, the deeper you are underwater, the higher the pressure. That's true even if the difference in depth is small, as it is in the pot, where the convex surface makes the spinning water slightly deeper toward the outside. So at any given height above the bottom, the water pressure is lowest in the center and increases slightly toward the sides of the pot.

That difference in pressure creates a force directed toward the center. The inward force counteracts the centrifugal force and keeps the water from sloshing out of the pot. At the very bottom, however, friction between the liquid and the solid pot causes the deepest water to rotate slightly slower than the water above it. Because the bottom water spins more slowly, it doesn't experience quite as much centrifugal force. But the inward pressure force is just as strong at the bottom as it is higher in the pot. So here the inward force wins out.

The net result is that the water near the bottom is pumped toward the center, pulling the egg along with it. So the egg sits nicely in the middle, spinning gently as it gets poached to perfection.

Drop an egg into a pot of hot, still water, and you're likely to end up with something closer to egg-drop soup than a poached egg.

Stir the pot vigorously before the egg goes in, however, and a phenomenon known as Ekman pumping will gather the egg for you into a nice, compact mass at the center.

The annoying belches of a boiling thick sauce that leave the stove covered in splatter are a sure sign that things are starting to scorch at the bottom of the pot.

Burning a Thick Sauce

Water is such a convenient lubricant and solvent in cooking in large part because it doesn't burn. But many of the liquids that we boil and simmer, from a béchamel to a marinara, can and will burn, despite the fact that they contain lots of water. Two principal factors determine whether or not a sauce or puree will burn: the thickness of the liquid and the temperature of the pot.

Thick liquids do not distribute heat as quickly as thin liquids do. In a pot of thin liquid, hotter fluid at the bottom of the pan can rise rapidly toward the surface, which pushes cooler parts of the food down in turbulent cycles of convection. A thin liquid, in other words, largely stirs itself. The temperature never gets any hotter than the boiling point of water, and as the pot heats further, the turbulence and rate of evaporation simply speed up. The technical term for this behavior is **nucleated boiling**.

A thick liquid, such as a tomato *ragù,* behaves differently, for two reasons. First, concentrated sugars and other solids in the sauce increase the boiling point of the liquid. The ragù thus approaches the temperature at which it starts to burn.

Second, natural convection within the viscous sauce is so slow that hot spots begin to form on the bottom. Small bubbles of steam still form at the bottom, but they aren't buoyant enough to rise to the surface of the thickening liquid. The part of the sauce near the pan bottom grows increasingly superheated until the small bubbles become so numerous that they form into solid columns of steam that feed into big, sluggish bubbles. Occasionally one will break free and belch sauce all over the kitchen and the chef! This is a stage of boiling known as **slug-and-column boiling**.

The big bubbles are telltale signs that the water remaining in the sauce is superheating at the bottom of the pot to 110–130 °C / 230–266 °F or higher—temperatures high enough to cause the sugars and solids in that region to scorch. To boil a thick liquid without scorching, you have two options: increase convection by constantly stirring and scraping the pot, or lower the burner power, so the pan bottom doesn't get hot enough to burn the sauce.

For more on the several stages of boiling and how sugars and other dissolved solids affect the boiling point of water, see page 1·316.

Slug-and-column boiling kicks in when a thick, slow-flowing liquid becomes superheated at the bottom of the pot. Small bubbles of steam, lacking the buoyancy to lift off, eventually aggregate into columns that break up into oversized bubbles. Left uncontrolled, the superheating ultimately will burn the natural sugars in the sauce.

STEAMING

For more on the use of steam in home canning, see Canning, page 75. For the role of steam in water-vapor ovens and combi ovens, see chapter 8 on Cooking in Modern Ovens, page 150.

For large or thick pieces of food, the insulating effect of the air and water layers created by steaming doesn't matter much. That's because the major limiting factor in cooking big ingredients is how fast heat moves through the food itself, not how fast heat can penetrate the food surface. Boiling and steaming are thus about equally rapid methods of cooking hefty chunks of food.

Both Western and Asian cooking traditions have settled on steaming as the preferred method for cooking certain kinds of foods. In the Western kitchen, cooks commonly steam small pieces of vegetables or thin slices of fish and other seafood. In Asian cooking, vegetables are usually stir-fried, and meats, seafood, and dumplings are typically steamed. Both traditions limit steaming primarily to small pieces of food that fit easily into a steaming basket set into a pot or a wok. A notable exception is the practice of steaming whole fish, which avoids disturbing delicate flesh that might otherwise fall apart.

The intuition of most chefs—and the conventional wisdom expressed in most cookbooks—is that steaming cooks food much more quickly than boiling does. A cursory review of the physics of heat and steam would seem to support this view. Liquid water molecules absorb a tremendous amount of energy as they boil off into the invisible gaseous state known as steam. That energy is called the **latent heat of vaporization.** You can think of it as energy stored in the water vapor. When water vapor condenses on the cool surface of a piece of food, it releases its stored energy and heats the food. Condensation is the key to the cooking power of steam.

Because the transition from liquid to vapor requires so much energy, steam contains far more energy, gram for gram, than boiling water does. Amazingly, converting a kilogram of boiling water into steam requires *five times* as much heat as you need to bring a kilogram of freezing cold water to a boil. It stands to reason, then, that steaming would cook food faster than boiling does.

Yet our experiments have shown that, in most situations in which steaming is used in the kitchen, boiling would be faster (see Steaming? Allow Extra Time, page 73). The reason is that condensation actually slows down the cooking process rather than hastening it.

On surfaces that have any degree of roughness (i.e., nearly all foods), tiny droplets of condensation quickly combine to form a thin but uniform layer of water known as a **film condensate.** The film acts like a heat shield: it quickly cools to the temperature of the food it envelops, then dramatically reduces the ability of heat to flow from the steam into the food.

A second phenomenon slows the steaming of fruits and vegetables. In most produce, the tissue just beneath the surface is laced with pockets of moist air. Heat makes the air in these pockets expand and escape as the tissue collapses. Some of the expelled air gets trapped beneath the film condensate, creating a blanket of air between the food and the steam. The insulating properties of air surpass even those of water: air blocks the transfer of heat better than wood, cork, cotton wool, and foam insulation do. The result is that, for most produce, boiling is substantially faster than steaming.

THE CHEMISTRY OF

Steaming for Sweetness

Speed isn't everything. The advantages of boiling vegetables need to be weighed against one big disadvantage: boiling dilutes many of the natural sugars, salts, vitamins, and color pigments that we prize in vegetables.

So, although steaming may be slightly slower, steam blanching often yields a vegetable that looks or tastes better.

Consider carrots, which contain large amounts of the natural sugars sucrose, glucose, and fructose. All of those sugars dissolve readily in water and thus leach into the pot when carrots are boiled. But human taste buds are wired for sweetness. Lose the sugars, and the carrots seem bland. Far better to steam the carrots so that the sugars mostly remain in the food, where they belong.

Glazing is another good alternative to boiling. Add a knob of butter to a pot of carrots, cover, and let the vegetables cook in a combination of fat and their own sweet juices (see Covered Sautéing, page 58).

COOKING BELOW THE FOG

Ask some friends to show you steam: more than likely they will point to the wisps of cloudy vapor escaping from beneath the lid of their saucepan or rice cooker. But those wispy clouds are fog, not steam. Steam, by definition, is invisible. Because it is composed of hot air and individual water molecules flying around in a gaseous state, steam cannot be seen.

Fog, in contrast, is a mixture of water droplets suspended in air, similar to pollen or dust lifted by the wind. Fog looks like a gas because the droplets are typically minuscule—around 10–15 microns (millionths of a meter) in diameter. But it is actually a suspended liquid, not a gas. Fog appears white and opaque because the dense swarm of tiny droplets scatters light rays passing through the mist.

In the kitchen, fog and steam are intimately connected. Just as where there's smoke, there's usually fire, when chefs see fog, there's usually steam beneath it. Steam-filled bubbles popping to the surface of boiling water are another visible (and audible) sign that steam is present. Take these signals as a warning, too, because steam is dangerous. In industrial settings, accidental steam leaks can be almost instantly lethal, yet completely invisible, to unfortunate bystanders.

The distinction between steam and fog has profound culinary ramifications. Steam cooks food quite differently than warm fog does: it can transfer huge amounts of energy to food because it contains latent heat, which it deposits onto the food surface when it condenses. The water in fog, in contrast, has already condensed into liquid form, so it is hardly any better at conducting heat than plain hot air is.

To be sure, cooking in humid air has its advantages (see Cooking in Moist Air, page 154). But rapid heat transfer isn't one of them. So when you set up your steamer, be sure to put the food close to the boiling water, well into the steam zone, and far below the fog.

WHY STEAMING IS OFTEN SLOWER THAN BOILING

Most cookbooks describe steaming as a much faster cooking method than boiling. Because steam can be hotter than the boiling point of water and can carry large amounts of latent heat energy, this makes intuitive sense even to those unfamiliar with the underlying physics. But in this case, intuition misleads. In many cases, steaming takes longer than boiling to cook food to a target temperature.

There are good reasons besides speed to steam foods, of course. Compared with boiled vegetables, steamed vegetables retain much more of the natural sugars and salts that give them their distinctive flavors, more of the pigments that provide their attractive colors, and more of the vitamins that make them so healthful to eat. Steam blanching is also far easier than boiling to perform on large quantities of food.

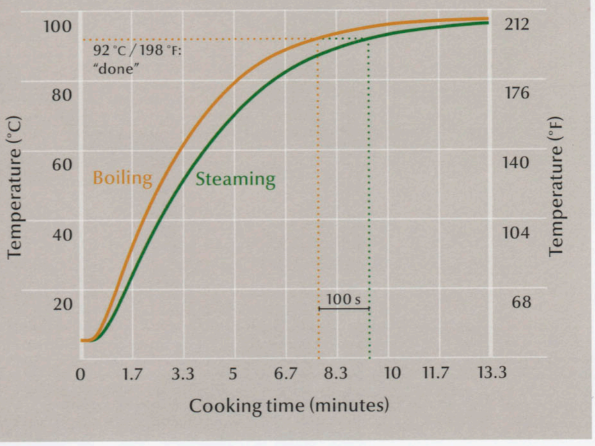
A tight-fitting lid is essential for steaming. A leaky cover allows cool air and fog to fill the pot while the invisible steam escapes. The lid also collects condensation, which drips back to the bottom and prevents the steamer from boiling dry.

Beads of water that form on the surface of the food are known as dropwise condensation. The droplets grow and merge to form film condensate, a thin layer of water that coats the surface, effectively insulating it from the hot steam. The watery film also traps air beneath it; together, these effects slow the cooking substantially.

Small pieces of food steam more quickly than large pieces do because they expose proportionally more surface area on which condensation can form.

Steaming? Allow Extra Time

Most cooks are surprised to learn that boiling actually cooks vegetables and fish faster than steaming does. We were, too—so we took out lab equipment to put it to the test. To control for variations in shape, size, and material composition, we machined several identical cylinders from solid aluminum, drilled holes through their exact centers, and inserted thermocouples. Then we capped the assemblies and used a data logger to record how the temperature of the cylinders rose as they were "cooked" in a pot of boiling water and in steam (not fog) in a pot with a tight-fitting lid. As the chart at right shows, the boiled probes consistently hit the target temperature well ahead of those in the steamer.



Droplets of condensation form on the thin walls near the top of the pot because the metal is cooled by the outside air to less than the boiling point of water.

Pack ingredients loosely into a steaming basket so steam can flow easily around them, distributing energy to all parts of the food.

Almost no condensation is visible on the wall midway up the pot. Here the sides are hotter than the boiling point of water. Condensation does form in this region on the cooler surfaces of the broccoli florets, however.

Bubbles splatter the bottom walls of the pot with water as they erupt, releasing steam that is slightly hotter than the boiling point of water.

CANNING

Napoleon Bonaparte once famously said that an army marches on its stomach—and he meant it! The logistic challenges of feeding his soldiers as they advanced across Europe spurred him to offer a 12,000-franc prize (a sizeable sum more than two centuries ago) for a new way to preserve fresh, ready-to-eat food. Enticing though this prize must have been, it must also have seemed well out of reach. After all, no new methods of preserving food had been devised in millennia.

At least one inventor wasn't dissuaded, however. Nicholas Appert had been a farmer and a cook, a pickler and a preserver, a wine maker and a brewer, and at the turn of the 19th century he was a confectioner in Paris. His successful solution to preserving food came from his observation that "if it works for wine, why not for food?"

What Appert meant by this was that wine keeps for decades in a bottle, as long as a cork keeps the air out. Appert figured that the same approach ought to work for food. His technique was simple: he filled a glass bottle with food, firmly stoppered it with a cork, then boiled it for as long as he deemed necessary to preserve the contents.

Appert quickly learned, however, that boiling is not always sufficient and that his method has dangerous limitations. Nevertheless, his invention was good enough to pass the French navy's tests in 1806 and for Napoleon himself to award Appert the prize money in 1809 (or perhaps 1810—the exact date seems to be controversial).

Napoleon was at war with England at the time, so the English government had no compunction about awarding a patent in 1810 to the Englishman Peter Durand for his "invention" of canning, really a stolen or leaked French military secret. The biggest difference between French *appertisation* and English canning was that Durand used sturdy, tin-plated cans rather than fragile glass bottles.

Amazingly, even as canning was being developed, no one understood why it worked. Nor did anyone know why boiling and sealing preserved only certain foods and not others. Keep in mind that microbes had yet to be discovered, and it would be another half century before Louis Pasteur identified them as the main cause of food spoilage.

And it wasn't until 1915 that USDA scientists identified the culprit that makes pressure canning the only safe way to can meats, seafood, and other low-acid foods: *Clostridium botulinum,* a hardy bacterium that survives normal boiling. Even absent a scientific explanation for botulism, however, pressure canners came into use as early as 1851. Indeed, it was Appert's enterprising nephew, Raymond Chevalier-Appert, who first showed that all foods could be safely preserved this way.

Napoleon was right that canning would be an important military technology. Canned foods were used during the Crimean War, the American Civil War, and the Franco-Prussian War. During World War I, the U.S. government urged citizens to grow and can their own food so the output of commercial canneries could be sent to troops overseas. Sloganeers beseeched citizens to "back up the cannon with the canner."

Ironically, however, the technology for mass canning didn't come soon enough to save Napoleon's own army. The emperor proved the validity of his own maxim during his disastrous invasion of Russia in 1812, when nearly three-quarters of the 690,000 troops he sent into Russia perished, the vast majority of them from starvation and disease. The retreating Russians had left no food behind for the invading soldiers, whose meager provisions spoiled even before reaching the front line.

Peter Durand's tin cans of food are reported to have read "cut round the top, near the edge with a knife, a chisel and hammer, or even a rock." It would be another 48 years before Ezra Warner invented the can opener in 1858!

The invention of canned food was a major milestone in food science and in the diet of millions of people. More recently, refrigerated and frozen food has provided alternatives, but canning still has its place as a food preservation technique. Although the result isn't quite the same as fresh food, it has its own virtues.

Boiling-Water Canning

Pressure-cooking was old technology, even in the 19th century. The French physicist and mathematician Denis Papin invented the pressurized boiler in 1679 and promoted his "digester" for cooking and other uses.

For more on the difference between sterilization and pasteurization, see Pasteurizing for Storage, page 249.

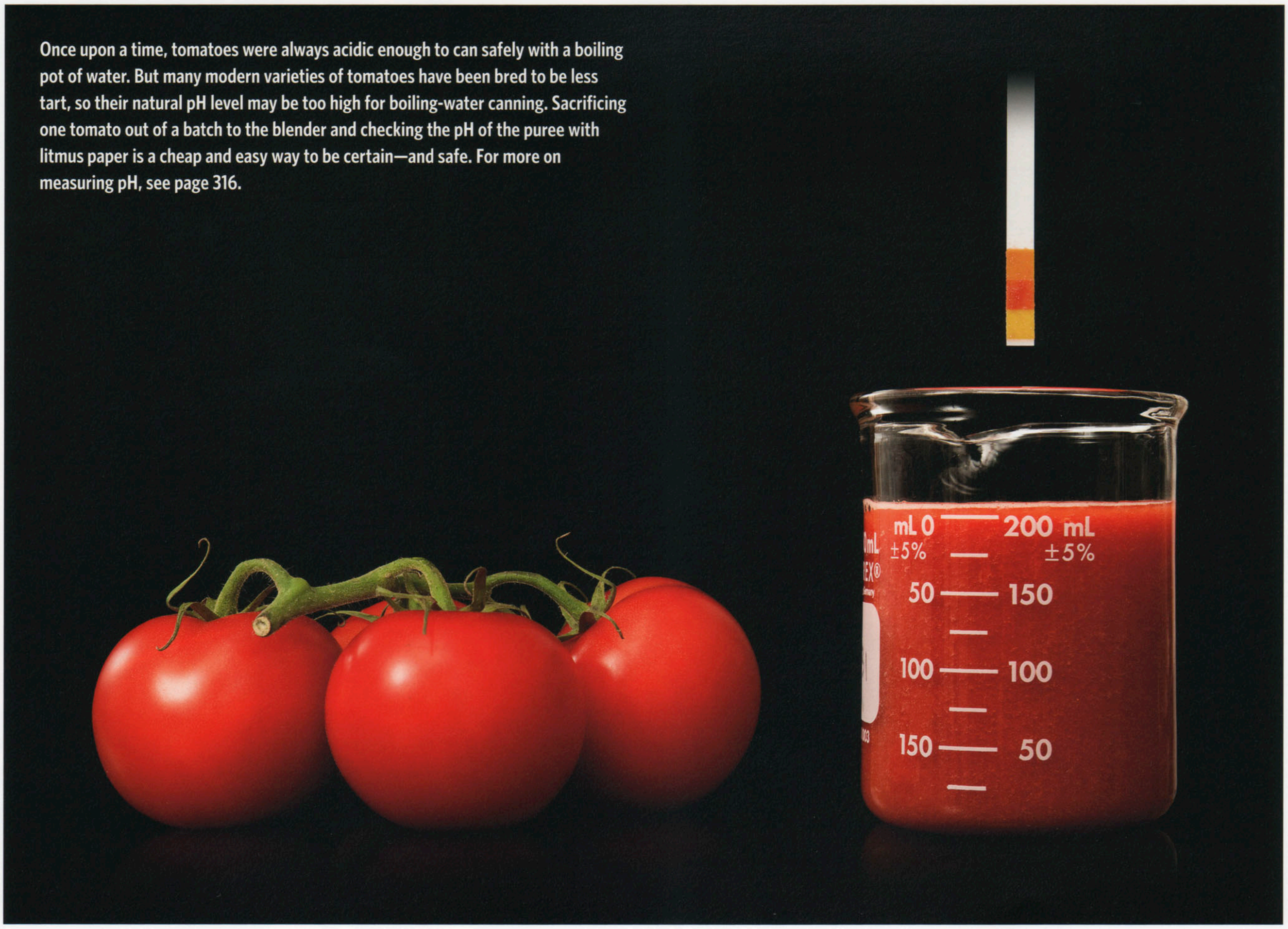
The most important part of canning is sterilization, which destroys the microorganisms that would otherwise quickly render most unrefrigerated foods unsafe to eat. This step also inactivates the natural enzymes within food that tend to ruin its color, flavor, and texture during storage.

To preserve food this way, you can use either boiling-water canning or pressure-canning. The deciding factor is the acidity of the food. Because of the lower temperature of boiling-water canning, the food must have a pH below 4.6; in all other cases, pressure-canning is the only safe choice. The pH of most fruits lies below this threshold, although that of some, like tomatoes and figs, may not and should therefore be tested.

The best way to test the acidity of a fruit is to check a pureed sample with a pH meter or litmus paper. If the pH is at 4.6 or just a little over, you can add vinegar, lemon juice, or even vitamin C (ascorbic acid) to bring the pH down to a safe level.

It's important, however, that the food be uniformly acidic. It isn't safe to use boiling water to can pasta in a tart tomato ragú; the pH of the pasta is too high. Cucumbers similarly aren't acidic enough to can whole without pressure. But if they're sliced and cooked in a pickling solution, they absorb enough of the acidic (and usually salty) brine to become uniformly sour. Sterilization with nothing more than ordinary boiling water is then safe.

Although there are dangers, there is no fundamental reason that you can't do your own canning safely at home. You just need to use the appropriate technique and to monitor times and temperatures carefully.


Once upon a time, tomatoes were always acidic enough to can safely with a boiling pot of water. But many modern varieties of tomatoes have been bred to be less tart, so their natural pH level may be too high for boiling-water canning. Sacrificing one tomato out of a batch to the blender and checking the pH of the puree with litmus paper is a cheap and easy way to be certain—and safe. For more on measuring pH, see page 316.

Package with Care

Before being sterilized, food should be packaged with an airtight, durable seal. Whether you put the food in traditional glass jars or in modern plastic retort bags, make every effort to get a clean seal. Take care not to fill jars so full that their contents might boil over, leaving food on the lip and preventing the lid from seating properly. (Sweet jams and jellies are less likely to boil over because their high sugar content raises the boiling point of the water in the jar.)

On the other hand, if the jar isn't sufficiently full, a tight seal may never form. The two-piece lid, common to most canning jars, is designed to allow expanding water vapor from the food to force out all of the air in the headspace above. When the jar cools, the water vapor condenses back into liquid water, leaving the headspace devoid of air. That vacuum holds the lid on snugly. If the jar isn't sufficiently full, air—rather than water vapor—could remain in the headspace and prevent the lid from sealing tightly. A change in food color during storage is a telltale sign that air remains in the jar.

A heating cycle isn't the only way to seal the lid of a canning jar. You can also use a vacuum chamber. Simply place the jar in the chamber and rest the lid on the jar. When the chamber is evacuated, air leaves the headspace. Once you restore pressure to the chamber, the weight of the atmosphere will seal the lid firmly against the glass.

There are two general approaches to filling jars for boiling-water canning: raw packing or hot-packing. If you pack food raw, it is crucial to also add enough liquid to ensure even heat transfer during sterilization. It's best to add liquid that is as hot as possible because its heat will raise the temperature of the food quickly.

Hot-packing is almost always the better tactic, however. Raw food takes a long time to warm up once it is inside the jar, and during that warming time natural enzymes can discolor many foods. If instead you blanch, steam, or parcook the food while stirring it in a pot, you can quickly destroy those enzymes and preserve an appetizing color.

The traditional glass canning jar is inexpensive, widely available in assorted sizes, and reusable. It does have some drawbacks, however: glass is breakable and slow to transfer heat when used for cold-packed food. The sealed jar also offers no easy way to monitor the core temperature of the food inside.

HOW TO Pack Food in Canning Jars

Although some health authorities cringe at the thought of people canning food at home, safe canning procedures are not difficult to follow. Sterilizing the food properly is essential. But you'll be wasting your efforts if you don't give equal attention to packaging the food securely so that microorganisms cannot sneak in. Cooks most commonly pack food in traditional glass jars, which have the added benefit of adding a bit of old-time character to your pantry shelves!

An alternative is to seal the food in special bags, a process called flexible-retort packaging. For a step-by-step guide to this approach, see How to Vacuum Pack Food with a Chamber Sealer, page 218. Plastic retort bags are less complicated to use than jars, but only special plastic retort packaging should ever be used for this style of canning. Standard sous vide bags typically will not withstand the high temperatures needed for sterilization, nor are they truly airtight for long periods of time.

1 **Clean the jars and lids (not shown).** Wash them, then sterilize them in boiling water. Discard any jars with chipped or scratched rims, and ensure that the rubber gaskets are intact.

2 **Check the ingredients.** Do not include bruised or damaged pieces, which are more likely to harbor harmful bacteria that might survive the canning process. If you will be canning with boiling water, ensure that the food is sufficiently acidic (i.e., has a pH less than 4.6).

3 **Choose whether to pack hot or raw (not shown).** Delicate fruits or vegetables can be packed raw. Parcook other foods, especially vegetables that tend to discolor when heated slowly, before placing them in the jars.

4 **Fill the jars.** If raw-packing, place the food in sterilized jars, then add enough boiling-hot liquid to fill in any air gaps and completely submerge the contents. If hot-packing, heat the jars in a pot of boiling water while parcooking the food. When the food is simmering hot, work quickly to drain the jars, then fill them with the food while it's very hot. Add extra cooking liquid as needed to fill any voids.

5 **Check the headspace.** For jams and jellies, leave 7 mm / ¼ in of headspace above the food. For all other foods, leave 13 mm / ½ in. Underfilled jars could lead to an interior vacuum that is too weak to hold a strong seal. Overfilled jars may boil over, leaving material on the rim, which could also interfere with the seal.

6 **Screw the lids on (not shown).** Wipe the rim of the jar, clamp the lid on tightly with the screw-on ring band, then loosen the ring band slightly so that air can escape during heating.

How Hot and How Long?

Whether the food is packed raw or hot, once it is properly sealed in its packaging, it must be kept hot enough long enough to destroy all pathogens. But just how hot is that? And how long do you have to cook things? Unfortunately, the answers to both of these questions depend on many factors.

For raw-packed jars and retort bags, the heating requirements hinge on how long it takes for all parts of the food to reach the minimum sterilization temperature. The geometry of the food, the size of a package, the number of packages being heated at once, even the nature of the added liquid all influence the rate of heating. With glass jars, it is so difficult to answer these questions that the U.S. Department of Agriculture (USDA) has produced only a handful of recipes for jars of specific sizes and shapes. These instructions work provided that you follow them *to the letter*.

The alternative is to sacrifice a jar of the food you are canning in the name of science. Leave the lid off and mount a thermometer probe so that the tip stays in the dead center of the jar. If the food in the jar is chunky, stick the tip of the thermometer into the core of a chunk at the center of the jar; don't leave it in the surrounding liquid, which heats faster. Wait until the probe shows that the food at the center of the test jar has reached the sterilization temperature, and then begin counting down the heating time needed to destroy any microbes.

Temperature monitoring is more straightforward when hot-packing, which is why we prefer that strategy. By bringing the food to a simmer in advance, adding it to hot jars, then quickly sealing the jars and submerging them in boiling water, you can be sure that all of the contents of the jars are at sterilization temperature from the get-go. Consequently, the filled jars only need to be heated long enough to destroy all of the pathogenic bacteria.

Guidelines published by the USDA say that foods suitable for boiling-water canning (those with a pH less than 4.6) must be sterilized at 100 °C / 212 °F for anywhere from five minutes to more than 90 minutes. So why does the USDA provide a seemingly random assortment of different canning times? We don't know for certain, but we have some hunches.

For starters, very little new research on canning acidic foods has been published since the 1950s, and what does appear in the literature from long ago is so confused and unclear that experts today are unable to identify the specific pathogen that was monitored in the original studies. The USDA seems to have collected an assortment of traditional recipes that work safely and to have disseminated these instructions without attempting to provide a scientific rationale for them.

Another possible reason for the scattershot nature of the official advice is a perfectly reasonable concern that, when confronted with an abundance of fruits and vegetables to be preserved, a person canning at home might be tempted to cut corners. A home cook might improperly pack the jars and overcrowd them into the cooking pot,

It is easier and less wasteful to check the temperature of food while canning if you package it in a flexible retort bag rather than a jar. You can remove the bag periodically from the boiling water, massage its contents to even out hot and cold spots, and then fold it over the tip of a thermometer to check the temperature.

It is imperative to be certain that there are no cold spots in the jar during the sterilization step. For raw-packed food, heating time must be added to the sterilization time to ensure this. How much extra time is required? It depends on a number of factors, but to be certain, sacrifice a jar of food so that a temperature probe can monitor the rising core temperature.

When pickling low-acidity vegetables such as cauliflower, allow extra time during the canning step for the pickling solution to diffuse all the way to the center of the food. Until diffusion is complete, sterilization cannot begin. If there is any uncertainty about how evenly vegetables have been pickled, pressure canning is the safer approach to use.

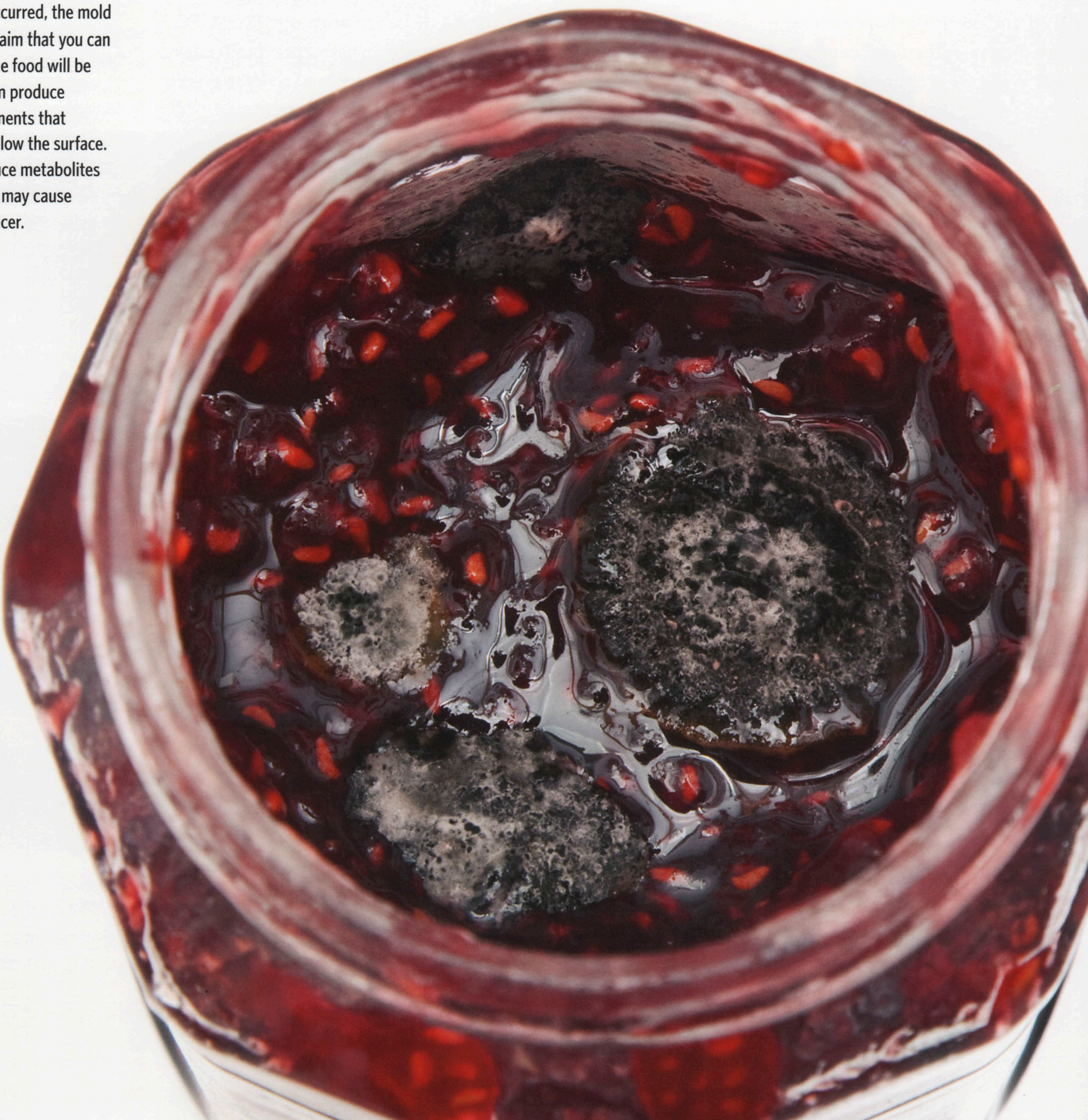
which would slow heating and lead to inadequate sterilization. To guard against mishap, the USDA built large margins of safety into its officially approved recipes—or so we surmise.

To determine safe heating procedures for boiling-water canning from first principles, you would need to identify the most difficult pathogen to destroy. Unfortunately, no one seems to have a clue what that is. So the only sensible procedure is to choose the USDA's minimum recommended boiling time, which happens to be five minutes, and to ensure that *all* of the food reaches 100 °C / 212 °F before counting down.

People canning foods at altitudes significantly above sea level, where the boiling temperature of water is diminished, need to use commensurately longer sterilization times: 10 minutes at altitudes between 300–1,830 m / 1,000–6,000 ft, and 15 minutes at altitudes higher than this. Alternatively, pressure canning can be used to shorten the sterilization time by raising the boiling point of the water.

The minimum sterilization time is just that, a minimum. Be sure to allow additional time for food at the center of the jars to heat up. For raw-packed foods, this step can add an hour or more to the cooking time. If you are pickling and canning in the same step, that requires extra time as well: an additional 5–10 minutes for porous foods such as cucumbers and sweet peppers but much more for dense vegetables such as beans, peas, and root vegetables.

If you open a jar of canned food and see mold on the surface, the food is bad; toss it out. This is particularly true for jams and jellies. Had sterilization occurred, the mold would not be there. The claim that you can scrape the mold off and the food will be safe is a myth. Molds often produce microscopic, root-like filaments that penetrate into the food below the surface. These filaments can produce metabolites known as mycotoxins that may cause genetic mutations and cancer.



HOW TO Sterilize Acidic Canned Foods in Boiling Water

Any food that has a pH of less than 4.6 can be adequately sterilized at 100 °C / 212 °F by using ordinary boiling water. You may have to sacrifice some of the food to the blender to test its pH, however. Dip the probe of a pH meter or a piece of litmus paper into the resulting puree. Add vinegar, lemon juice, or even vitamin C (ascorbic acid) if you need to lower the pH. Canning cucumbers this way, for example, is unsafe, whereas canning pickles is perfectly fine.

1 **Preheat the water (not shown).** Warm the water in the pot to near boiling to avoid cooling the food in the jars. Stop short of a vigorous boil, however, so you don't scald yourself as you add the jars.

3 **Keep it boiling (not shown).** Make sure that the water always remains boiling hot. Monitor the core temperature of the food, if necessary, by using the technique described on page 79.

4 **Sterilize the food (not shown).** The minimum sterilization times shown in the table are just that, minimums. If there is any possibility that the food in the packaging wasn't at boiling temperature for the full time, keep heating it.

Minimum Sterilization Times

Elevation		Sterilization time
(m)	(ft)	(min)
0–300	**0–1,000**	**5**
300–1,830	**1,000–6,000**	**10**
above 1,830	**above 6,000**	**15**

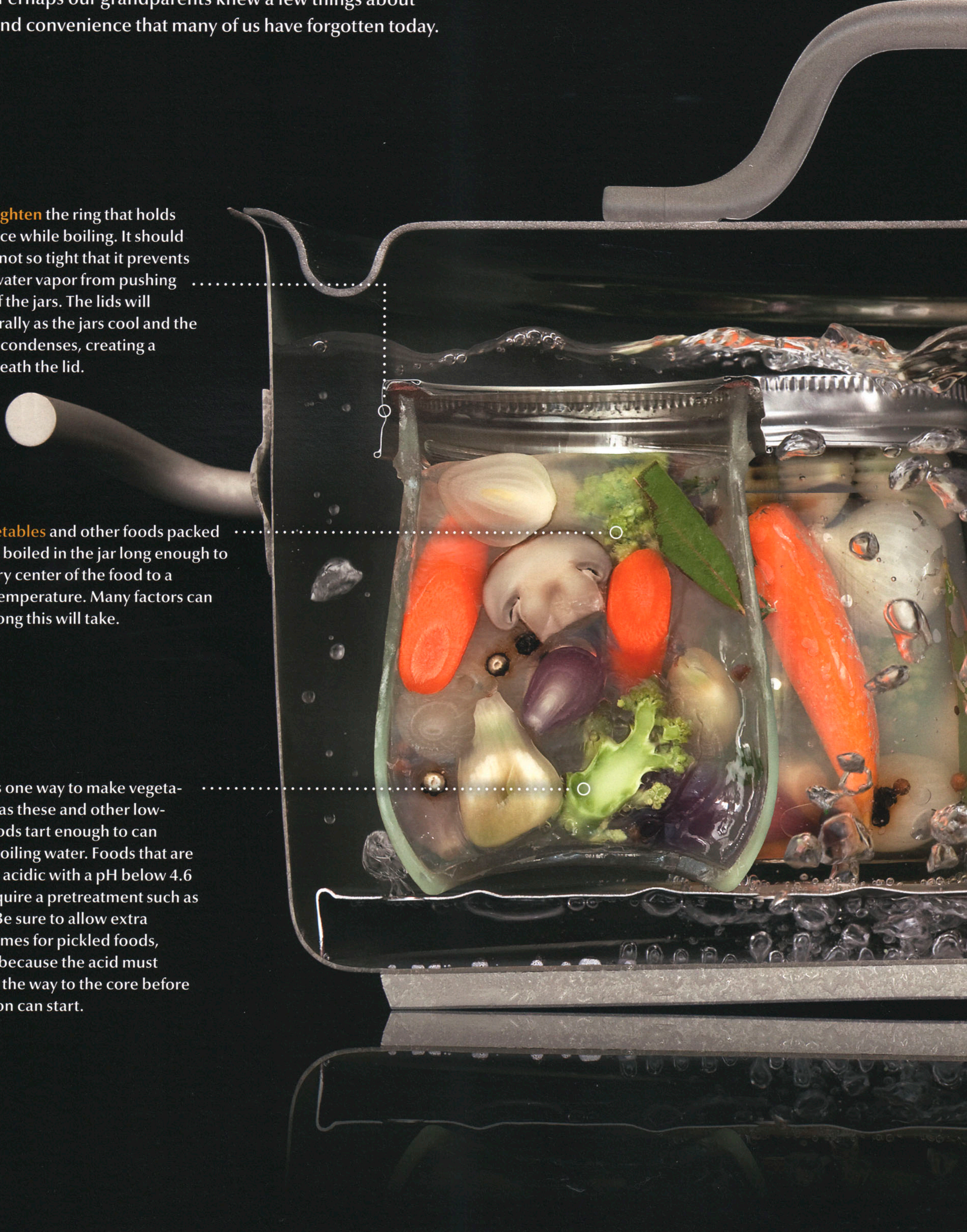
2 **Submerge the jars.** Use a canning rack to hold the jars off the bottom of the pot so that water can circulate freely underneath. At least 5 cm / 2 in of water should cover the jar tops at all times.

5 **Cool.** After sterilization is complete, remove the jars, and let them cool upright and undisturbed. The vacuum that holds the lid tight won't form until the jars cool and the water vapor inside condenses.

6 **Unscrew the ring bands, and test the tightness of the lids.** To double check, place each cooled jar on its side, and roll it back and forth to see whether any liquid leaks out.

BOILING TO PRESERVE OR PICKLE

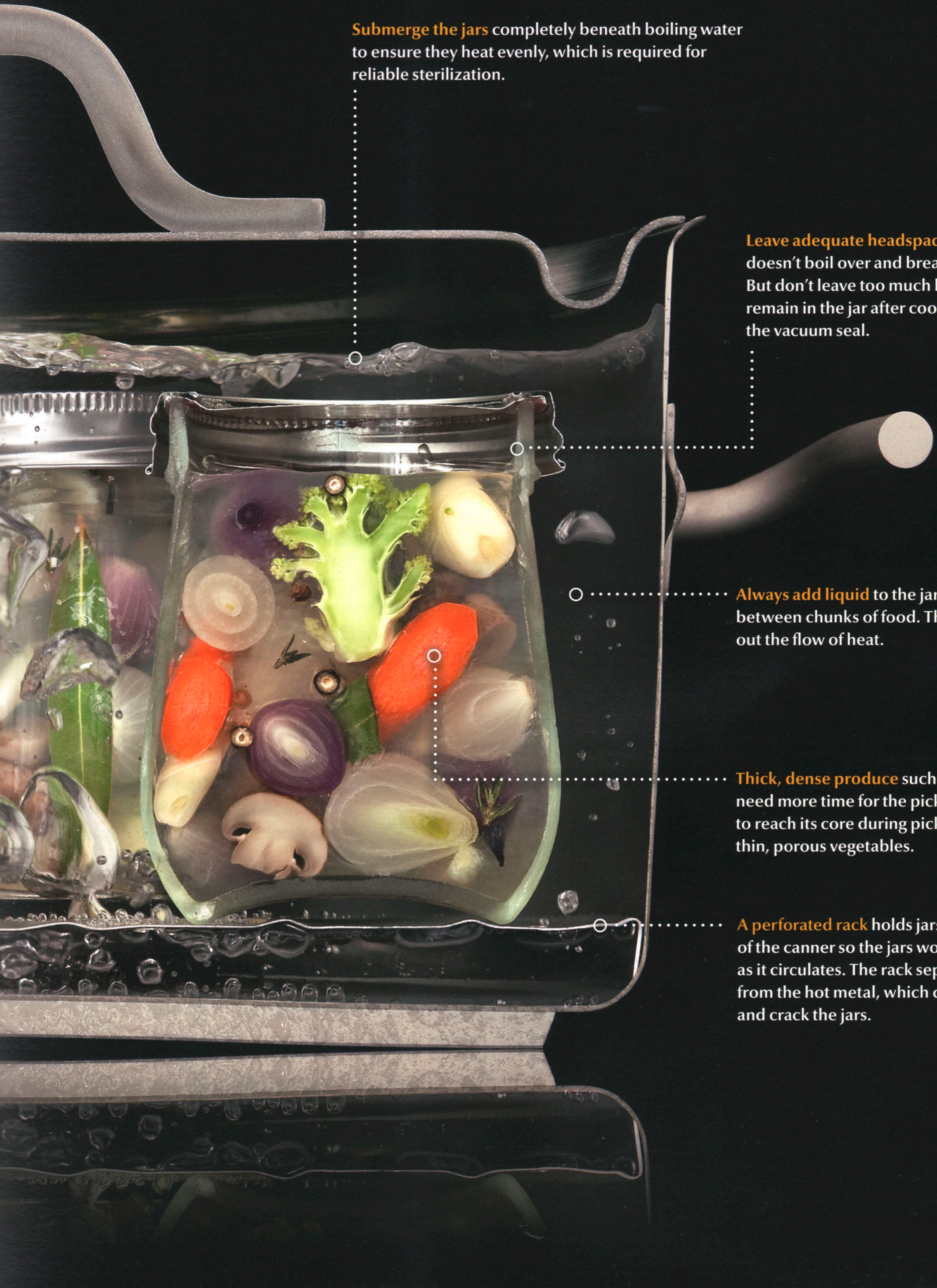
Originally an invention of such importance that it was kept a military secret, canning is seen as old-fashioned by many of us today. This is too bad; canning in a pot of boiling water is still an easy way to preserve an abundance of fruits and some vegetables for another time of the year. Not only is it economical, but enjoying the burst of flavor from summer's berries in the dead of winter is no small pleasure. Perhaps our grandparents knew a few things about frugality and convenience that many of us have forgotten today.



Don't overtighten the ring that holds the lid in place while boiling. It should be snug but not so tight that it prevents expanding water vapor from pushing the air out of the jars. The lids will tighten naturally as the jars cool and the water vapor condenses, creating a vacuum beneath the lid.

Pickled vegetables and other foods packed raw must be boiled in the jar long enough to bring the very center of the food to a simmering temperature. Many factors can affect how long this will take.

Pickling is one way to make vegetables such as these and other low-acidity foods tart enough to can safely in boiling water. Foods that are uniformly acidic with a pH below 4.6 do not require a pretreatment such as pickling. Be sure to allow extra cooking times for pickled foods, however, because the acid must diffuse all the way to the core before sterilization can start.



Submerge the jars completely beneath boiling water to ensure they heat evenly, which is required for reliable sterilization.

Leave adequate headspace so that the food doesn't boil over and break the airtight seal. But don't leave too much headspace, or air will remain in the jar after cooling and will weaken the vacuum seal.

Always add liquid to the jars to fill in voids between chunks of food. The liquid helps even out the flow of heat.

Thick, dense produce such as carrots need more time for the pickling solution to reach its core during pickling than do thin, porous vegetables.

A perforated rack holds jars off the bottom of the canner so the jars won't hinder water as it circulates. The rack separates the glass from the hot metal, which could overheat and crack the jars.

For more on suitable time and temperature combinations for pasteurization of food, see page 1·182.

Frigi-canning

The quality of most canned vegetables was the inspiration for a refinement of the canning process made by E. F. Kohman in 1960. Known as frigi-canning, Kohman's idea was to go halfway to canning. Freshly picked vegetables were packed into glass jars. Rather than sterilizing the vegetables by cooking them at high temperatures for long times, however, Kohman instead cooked the jars in water baths just hot enough to destroy most vegetative forms of bacteria and to halt the slow damage that enzymes cause to the food.

Because the food isn't sterilized by this process, the jars must be refrigerated to avoid the growth of toxic anaerobic bacteria—hence the name frigi-canning. Refrigeration serves a second important purpose as well: it slows chemical reactions that generate off-flavors. When frigi-canning is properly done, vegetables will keep in the refrigerator for weeks to a few months while retaining most of their freshly cooked quality.

These days, flexible sous vide packaging has replaced the need for fragile glass jars, and frigi-canning is now known as cook-chill sous vide.

We have Kohman and frigi-canning to thank in part for the ubiquity of fresh milk. Today we take this staple for granted, but before the 1960s, the distribution of fresh milk to an increasingly urban population was a serious technical challenge. At one point, milk was even adulterated with formaldehyde to extend its shelf life during its trip through the distribution chain! Kohman developed frigi-canning in part to solve this problem—and it has.

Pasteurized products are so ubiquitous today that it's hard to imagine a time without such technology. But pasteurization didn't exist until the French chemist Louis Pasteur first developed the process—at the command of Emperor Napoleon III—to keep wine from spoiling.

Pasteur began his chemistry career by studying organic crystals. In 1854, he became dean of chemistry at the University of Lille, a town that was home to several distilleries and factories. The university encouraged its professors to research problems faced by these local industries. In 1856, Pasteur began working to help a nearby distiller address his difficulties in making alcohol from beets.

As Pasteur investigated the fermentation process, he made the groundbreaking discovery that it is yeasts—living organisms—that turn sugar into alcohol, whereas other microorganisms spoil food by producing undesirable flavors. Before Pasteur's insight, most scientists believed that yeasts were merely by-products or catalysts of fermentation.

Some 50 years after Nicholas Appert developed the canning process for Napoleon Bonaparte (the uncle of Napolean III), Pasteur's discovery finally provided a scientific rationale for how canning preserves food: it destroys the microorganisms that spoil food and cause illness.

In 1863, an aide to Napoleon III sent Pasteur a letter commissioning him to study both the diseases affecting wine and issues in wine preservation. Such matters were of substantial economic importance to France, particularly during the grape harvest.

A year later, building on his earlier discoveries, Pasteur developed the process that would immortalize his name: the application of heat to achieve a specific temperature for a specified time to greatly reduce the number of spoilage microbes in the

Fresh vegetables in a juice are a good candidate for frigi-canning.

A water bath is not suitable for conventional canning but is ideal for frigi-canning, which is essentially just cook-chill sous vide done in jars.

wine. Unlike the temperatures used for canning, the temperatures used by Pasteur were far below the boiling point and therefore far less detrimental to the quality of the wine.

During the 20th century, reliable refrigeration became ubiquitous and made it possible to apply the principle of pasteurization to greatly extend the refrigerated shelf life of dairy products, fruit juices, and many other fresh foods. Indeed, without pasteurization, much of the modern food industry would not be possible.

Pasteur is also known to medical science as one of the inventors (along with Edward Jenner) of vaccination. Between pasteurization and vaccination, Pasteur's discoveries have saved millions of lives.

Pressure-canning

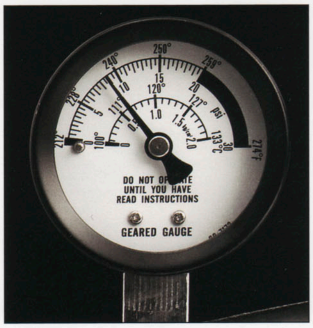
A third method of canning is pressure-canning, which is required for low-acidity (high-pH) foods. This category includes almost all vegetables, meats and seafood, soups and sauces, and most other prepared foods that haven't been dried, pickled, or preserved with high levels of salt, sugar, or alcohol.

Pressure canning is used for commercial sterilization, which is typically designed to disable all actively reproducing microbes as well as 99.9999999999% of any *C. botulinum* spores in the food. (Spores are ultrahardy, seedlike bodies that the bacteria make when stressed.) Put another way, a spore has only a one-in-a-trillion chance of surviving in the canned food.

Yeasts, molds, and most bacteria die at temperatures well below 100 °C / 212 °F, the boiling point of water at sea level, but to eliminate *C. botulinum spores* you must hold them at temperatures of 115 °C / 240 °F or hotter. The exact temperature depends on heating time and other factors, such as the pH of the food. The only way to heat food to these temperatures without drying it out is to use a pressure canner or an autoclave. The mantra of low-acid, high-pH canning is "to increase the temperature, increase the pressure."

Not all pressure cookers should be used for pressure canning, however. An ordinary pressure

The reduction in pathogens that results during canning is called a 12D reduction—see page 1·148.



A pressure gauge is the only reliable way to know the temperature inside a pressure canner, but it can mislead the naive.

Spring-loaded valves are common on pressure cookers and generally unsuitable for canning because they can prevent proper venting and become inaccurate over time as the spring fatigues.

cooker lacks a pressure gauge. Nor does it include a calibrated weight to seal the canner. These features are absolute requirements for safe pressure canning. Proper pressure canners include both accessories—but it is crucial to understand just when you should place the weight on the canner as well as the several ways in which the pressure shown on the gauge can fool you.

The Lies a Gauge Will Tell

Perhaps surprisingly, a canner's pressure gauge doesn't measure absolute pressure. Rather, it measures how much the pressure inside exceeds the surrounding atmospheric pressure. This fact means that it will read zero when a cold canner is first sealed, even though the pressure inside the pot is obviously well above zero. At sea level, it's about 1 bar / 14.7 psi. At higher altitudes, atmospheric pressure is less, but the pressure gauge on a freshly sealed cold canner will always read zero.

The needle on the gauge will begin moving only once you apply some heat. As the water inside gets hotter, water vapor rises to mix in the headspace with the air that was sealed inside initially. With continued heating, the hot air and water vapor eventually will push outward with enough force to bring the reading to 1 bar / 14.5 psi of *gauge pressure* (sometimes abbreviated psig).

Be careful here: this reading indicates the amount of pressure above the surrounding atmospheric value. The absolute pressure inside the cooker—which is what determines the temperature at which the water inside will boil—is the gauge pressure *plus* the surrounding atmospheric pressure. At sea level, this means that the total pressure pushing down on the water inside the pressure cooker is about 2 bar / 29 psi.

The boiling point of water under 2 bar / 29 psi of pressure is very close to 120 °C / 248 °F and, if the pressure gauge has a temperature scale, it will show that temperature. But what if you're at some elevation higher than sea level? Then the absolute pressure inside the canner will be less than 2 bar / 29 psi (because atmospheric pressure drops at higher elevations), and the water inside will be boiling at some temperature lower than 120 °C / 248 °F.

In mile-high Denver, for example, water boils in the open at about 6 °C / 11 °F less than it does in coastal Miami, so a cook in Denver should expect the water in her pressure canner showing 1 bar / 14.5 psi of gauge pressure to be boiling at 114 °C / 237 °F—regardless of what the temperature scale on the gauge suggests.

The gauge on a pressure canner can trick you in other ways, too. Some pressure canners and most pressure cookers have a spring-loaded valve that is normally open and allows air to escape from the headspace. As heating begins, expanding vapor pushes this valve up, closing off the vent. (At very high pressures, it rises farther and opens the vent back up again.) Unfortunately, the valve always closes too soon and leaves some air trapped in the headspace.

Having a mixture of air, water, and steam all interacting under pressure is a bad thing because it makes it impossible to know the actual temperature of the water with any degree of confidence (see How Air Confounds Pressure Canning, next page). The solution is to always vent the air from the headspace in the pressure canner as it heats up, so only steam is left to fill the headspace.

Some manufacturers of spring-loaded canners say that venting is not necessary. The USDA, however, says that *all* pressure canners must be vented for the very reason that we have just explained—you can't sterilize food properly if you don't know the temperature of your water bath and the steam above it. Pressure cookers are difficult to vent manually, and that is the main reason that we don't recommend using them for canning.

Proper pressure canners are easy to vent because they use a calibrated weight rather than a spring-loaded stopcock. When using one, you bring the water inside to a simmer, then add the packaged food and replace the lid. With the calibrated weight removed, you boil the water for 10 min to create enough steam to force all of the air out the vent hole, leaving only pure steam in the headspace. You then place the calibrated

weight on the vent, allowing pressure to build rapidly inside the canner.

If you follow these steps, the space inside will contain pure steam, and the measured pressure will accurately reflect the temperature. You'll be canning safely in another way as well because the weight is not heavy enough to allow you to pressurize the canner to dangerous levels.

Pressure cookers with spring-loaded valves are often a better choice for stock- and sauce-making precisely because the valve seals the cooker before it is vented. This action traps most aromatic volatiles before they can be ventilated away. It might not seem as if this would make a substantial difference, but, in several controlled experiments by Dave Arnold and Nils Norén at The French Culinary Institute, pressure-cooked stock prepared in unvented cookers was always preferred by the tasting panel of professional chefs. For more on pressure-cooked stocks, see page 293.

THE PHYSICS OF

How Air Confounds Pressure Canning

It's important for safe canning to get the air out of the pressure vessel as it heats up. Remember, the only information you have for determining whether the temperature is sufficient for sterilization is the reading on the pressure gauge. From this number, you can estimate the boiling point of the water inside the canner. But is the water in fact hot enough to boil?

If the pressure is constant, and steam isn't billowing from the canner, you can be sure that the water is *not* boiling. But you will not know whether the temperature of the water is just a little or a lot below its boiling point for that pressure.

To avoid this uncertainty, vent the air above the water before sealing the pressure canner. The pressure will then increase from pure steam alone. This simple maneuver solves the problem because water of a given temperature has a well-determined vapor pressure. This is the pressure at which there will be as many water molecules evaporating from the water's surface to become steam as there are molecules in the overlying steam returning to the water.

If the pressure in your canner is constant, the water and steam inside will be in such an equilibrium. And the vapor pressure of the water, by definition, will equal the pressure of the steam. So if you know this pressure, you easily can look up the temperature of the water. If it were any hotter than this value, more water would evaporate, increasing the pressure. If the temperature were any lower, some of the steam would condense, lowering the pressure.

But how do you find the pressure of the steam? If it is the only gas in the canner, the answer is easy: it's the gauge pressure plus the surrounding atmospheric pressure. If, however, the canner contains a combination of steam and air, the total pressure inside is a combination of the partial pressure of the various gases.

Dalton's law of partial pressures states that the total pressure of a gas mixture is equal to the sum of the partial pressures of its constituents. For example, if a pressure canner at sea level contains a mixture of 50% air and 50% steam at a gauge pressure of 1 bar (hence an absolute pressure of 2 bar), the vapor pressure of water inside will be just 1.5 bar of gauge pressure. So the water and steam will be at just over 111 °C / 232 °F, which is not hot enough to sterilize the food safely—even though the gauge suggests the temperature is a safe 120 °C / 248 °F.

Without venting the canner at the start, you will have no way of knowing what the proportions of air and steam are. Thus you would not know the partial pressure of the steam—and hence the temperature of the water and the steam. All you would know is that the partial pressure of the steam is something less than the pressure you determined from the gauge, meaning that the temperature of the water and steam must be something less than it would be had the headspace been filled only with steam.

The bottom line is simple: always vent the air from your pressure canner.

What Pressure and How Long?

Once you vent the canner and bring it to the desired pressure—and thus the desired temperature—all you need to do is hold it there long enough to ensure a trillion-fold reduction of *C. botulinum* spores. So how long does that take? As with boiling-water canning, it depends.

Even if you preheated the food to 100 °C / 212 °F before you packed it, it needs time to heat up to its final sterilization temperature. How much time depends on many variables: the starting temperature of the food; the thermal conductivity of the bags or jars that contain it; the size and number of the containers; the size of the pressure canner itself; and the speed at which your burner can bring the pot to full pressure.

Nevertheless, we can offer some general guidelines. Let's divide canned foods into three categories: fully convecting, semiconvecting, and conducting. Convecting foods are basically liquids: juices, stocks, or thin sauces in which any hot or cold spots that develop during canning quickly even out through natural convection.

The semiconvecting category includes solid chunks of food packed in a thin liquid, such as beans in water. Although the liquid will heat quickly, the temperature of the solids will rise more slowly, confounding our ability to estimate proper heating times. The conducting category includes everything else, from thick sauces like spaghetti sauce to potted meats. Foods in this category also heat slowly. In the following table, we offer some guidance on the typical times needed for packaged food to heat up in a canner as well as minimum temperature-and-time combinations needed to can food safely.

THE TECHNOLOGY OF

Fine Tuning the Process of Pressure Canning

Canning recipes typically build large margins of error into the recommended sterilization times because there is no easy, reliable way to predict how long a given pressure canner will take to raise the core food temperature inside a jar to the required level.

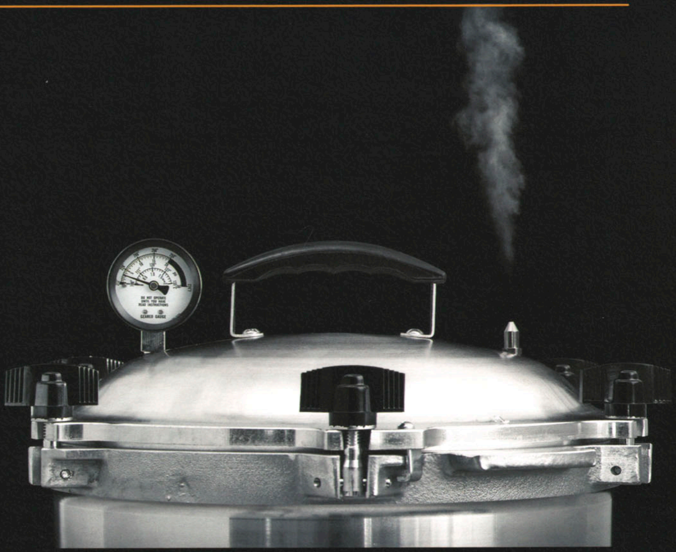
If you want to maintain the highest food quality by using the shortest canning time that is still safe, there is an alternative. You can install a thermometer in your canner so that you can directly sense when the jars reach the sterilization temperature. This is exactly what canning companies do when they develop a commercial canning process. And it is also what we did to gather experimental data for the table on the next page.

In our tests, we varied the food in the jars, the size of the jars, and the number and arrangement of jars in the canner. We also heated the canner slowly in some tests and quickly in others, and we vented the canner properly in some tests and skipped this step in others. Each of these factors affected the time needed to reach sterilization temperature. So the large safety margins are required for a canning recipe unless you do the experiments yourself, then keep everything about your process unchanged.

We built a pressure canner with multiple thermocouple probes to test temperatures in all phases of the canning process.

HOW TO Use a Pressure Canner

Preserving foods that are not acidic enough to be sterilized with ordinary boiling water requires a pressure canner, which heats to higher temperatures. Don't use an ordinary pressure cooker for this purpose because it will be difficult to vent properly. Only with proper venting at the start will you know for certain that the water inside is hot enough. For instructions on how to package the food for pressure canning, see How To Pack Food in Canning Jars on page 78.



1 **Place the jars.** Whether you add the food hot or cold, arrange the jars on a special canning rack at the bottom of the pressure canner (see next page). This rack allows water to circulate freely around the jars and prevents breakage. Leave some space between the jars; a crowded canner has trouble raising and maintaining steam pressure.

2 **Add water.** Use enough water to submerge the rack fully: 2–3 cm / 1–2 in is usually sufficient. Add a little more if the canner is very full or the expected sterilization time is longer than usual. Don't fill the canner entirely, however, because the steam above the water is what does the heating.

3 **Heat and vent.** Put the lid on the pressure canner, and tighten the fittings before you begin heating, but don't yet place the calibrated weight on the vent. When large amounts of steam and fog spout from this opening, the water is at a boil. Continue venting for 10 min before capping it with the weight.

4 **Continue heating the pressure canner until the desired pressure (and thus temperature) is attained.** Apply adequate heat to maintain this pressure, and allow enough time for the food to reach the target sterilization temperature, which varies with the size of the jar, the kind of food, and the packing temperature. Refer to the table below.

5 **Sterilize the food.** After the food has had enough time to heat fully, keep the canner at pressure for the necessary sterilization time. Hold either at **115** °C / **239** °F for 12 min or at **120** °C / **248** °F for 2½ min.

6 **Cool the canner (not shown).** After the sterilization time has elapsed, turn off the heat source, and let the pressure canner cool until the pressure gauge indicates zero. Then remove the weight from the vent, and open the lid. Be careful: escaping steam can cause a severe burn. If in doubt, let the pressure canner cool to the touch before opening it.

7 **Check the seals.** Let the jars cool completely, then examine the quality of the seals as described for boiling-water canning on page 81. For plastic retort bags, check for discoloration or damage to the plastic itself.

Time to Reach Sterilization Temperature

Food packed at		Sterilize to		237 ml / 8 oz	237 ml / 8 oz	473 ml / 16 oz	710 ml / 24 oz	946 ml / 32 oz
(°C)	(°F)	(°C)	(°F)	(min)	(min)	(min)	(min)	(min)
Convecting foods								
20	**68**	115	239	30	28	31	40	40
		120	248	44	41	45	58	58
90	**194**	115	239	17	16	18	23	23
		120	248	31	29	32	41	41
Conducting foods								
20	**68**	115	239	67	54	62	94	94
		120	248	92	75	85	130	131
90	**194**	115	239	44	35	40	60	60
		120	248	69	56	63	97	97

CRANK UP THE PRESSURE, TURN UP THE HEAT

Pressure canners are essential for safely canning any fresh food that has a pH higher than 4.6. Under pressure, water can get hot enough to destroy all traces of toxic spores that can grow in unrefrigerated, low-acidity food, even when it is hermetically sealed in a jar.

The drawback to a pressure canner is that it's impossible to see what's going on inside once the canner is sealed. A good pressure gauge is thus essential because it can tell you (with a little mental calculation) the actual pressure—and hence the temperature—of the hot steam that does the cooking. But beware: if you don't pay attention to what's *really* going on, then the gauge will tell dangerous lies.

The pressure gauge is an essential feature for safe pressure canning. But there are some tricks to interpreting what it tells you. You need to be aware of the external atmospheric pressure, for example, because that isn't factored into the reading on the gauge (see page 86).

Steam condensing on the jars does the heating.

Uncoated aluminum, used in the fabrication of most large canners, is inexpensive but suitable only for cooking food that has been packaged inside another container.

Food will swell inside a pressure canner much more than it would during boiling-water canning. These tomatoes, for example, have expanded enough to entirely fill the jars. To prevent the food from leaking and ruining the seal, always leave at least 2.5 cm / 1 in of headspace when packing a jar for pressure-canning.

Don't submerge the jars. Use only enough water to avoid running dry while the canner heats up, vents, and sterilizes.

A perforated rack holds jars off the bottom of the canner so that the jars won't hinder water as it circulates. The rack separates the glass from the hot metal, which could overheat and crack the jars.

A calibrated weight is another essential feature. Remove the weight to allow air to escape as the steam level rises.

Any air trapped inside the canner will mix with the steam, causing the temperature to be lower than that indicated on the gauge. How much lower is impossible to know. So always wait at least 10 min for air to vent from the canner before sealing it.

Leave space around the jars. In an overcrowded canner, steam condenses faster than it is produced, and as a result the food heats unevenly.

The very core of each and every jar of food must reach the ultimate sterilization temperature before you start the clock on the sterilization time. Because it is usually impossible to know for certain how long this will take, follow official guidelines that provide safety margins.

Tomatoes were once more than acidic enough for canning in boiling water. But the tartness has been bred out of modern hybrids, which often have a pH near or above 4.6. To be safe, process them in a pressure canner.

7

POT-ROASTING AND STEWING

The most complex of the traditional cooking methods is arguably braising, that combination technique that involves both dry and moist heat and in which heat conduction, convection, and radiation can all play critical roles. Even the terminology here is complicated: "pot-roasting" and "stewing" are sometimes used interchangeably with "braising" but sometimes connote differences in what kind of liquid—or how much of it—is added to the food.

A bit of history can help clarify the muddle. The noun "**braise**" comes from the French word for the dying embers of the day's fire. The related French verb *braiser* implies cooking slowly in a tightly sealed vessel that is heated from all sides. The closest counterpart in the Anglo-Saxon tradition to this traditional French technique is pot-roasting—that is, roasting an entire joint of meat in a covered pot over a fire.

Over time, the replacement of wood and coal fires in the kitchen with gas and electric burners led to a shift in the use of the terms braising and pot-roasting. Today, most cooks understand these to mean simply cooking food in added liquid, usually after an initial quick sear in a pan. Braising and pot-roasting have thus become synonymous with stewing.

That is unfortunate because meats braised or pot-roasted in the authentic way are subjected to a cooking environment that is qualitatively different from that experienced by meats that are simply stewed. The differences in flavor, although hard to describe, are real. In the hope of spurring cooks to recapture the lost art of pot-roasting, we present the details of the old method here before we turn to contemporary braising, which for the sake of clarity we'll refer to as stewing.

Pot Roast: The Authentic Braise

Once upon a time, cooks would fill a large cast-iron pot with assorted vegetables and meat, add just enough liquid to cover the bottom, place a cast-iron lid on top, then place the sealed pot on the embers of a fire. Typically, hot coals were piled on top of the lid. If large chunks of tougher meat were used in the recipe, this process was called braising; if instead a whole roasting joint was used, they called it pot-roasting.

Liquid was added to the pot for two reasons. First, many cooks believed it would keep the meat succulent and juicy. A probably more important reason, however, was that the fluid quenched hot spots that inevitably formed in the iron pot as it absorbed heat from the glowing coals below. First and foremost, the liquid was there to prevent the food from scorching.

It doesn't take much liquid to accomplish that goal. And, traditionally, it would have been unusual to add more than a shallow layer of water or other fluids. Drown the meat, after all, and the result will be closer to boiled beef than to pot-roasted sirloin!

The arrangement of an old-style pot roast may sound simple—just a bit of liquid in the pot and heat on both top and bottom—but it sets up a fascinating environment that cooks food in multiple ways at once (see The Lost Art of Pot-Roasting, next page). Heat radiating from the lid and sides of the pot, humid hot air swirling around the food in the middle, and simmering liquid on the bottom all contribute to the cooking and the distinct flavors of an authentic pot roast.

Sealing the pot with a lid is crucial for several reasons. First, radiant energy from the lid browns the top and sides of the meat. This process gives the meat an appealing color and creates Maillard flavor compounds that dissolve in the juices below. Without a lid, those aromatic chemicals escape in the air. Although their loss makes your kitchen smell wonderful, it deprives the sauce of some of its best aromas and flavors!

Second, the lid keeps the air in the pot humid. As a result, the food heats faster and dries out less. Third, high humidity helps to dissolve chewy

Modern cooking techniques allow cooks to nearly replicate the flavors and textures of authentic pot roast with far greater control than an open fire allows. Believe it or not, everything in this photo is edible: what look like ashes are three different kinds of garnish. For a plated dish that includes edible "ashes," see the recipe for Autumn Harvest Pork Roast, page 5·17.

THE LOST ART OF POT-ROASTING

In the original, authentic forms of braising and pot-roasting, cooks placed food with a small amount of liquid into an iron pot with a tight lid, set the pot directly on a bed of dying embers, and piled hot coals on top. This technique creates a surprisingly complex system that allows heat to move into the food in three distinct ways simultaneously: by radiation, by convection, and by conduction. Each of these modes of heat transfer is dominant in a different zone within the pot, and each is essential to creating the unique flavor of traditional pot roast.

RADIATION ZONE
Rays of infrared light shine from the lid and sides of the pot and onto the food. The radiating heat slowly dehydrates and then browns the upper surface of the meat. Juices leaking out of the browning food dissolve Maillard compounds that create the enticing aroma. These juices then carry these compounds to the bottom of the pot, where they collect and intensify.

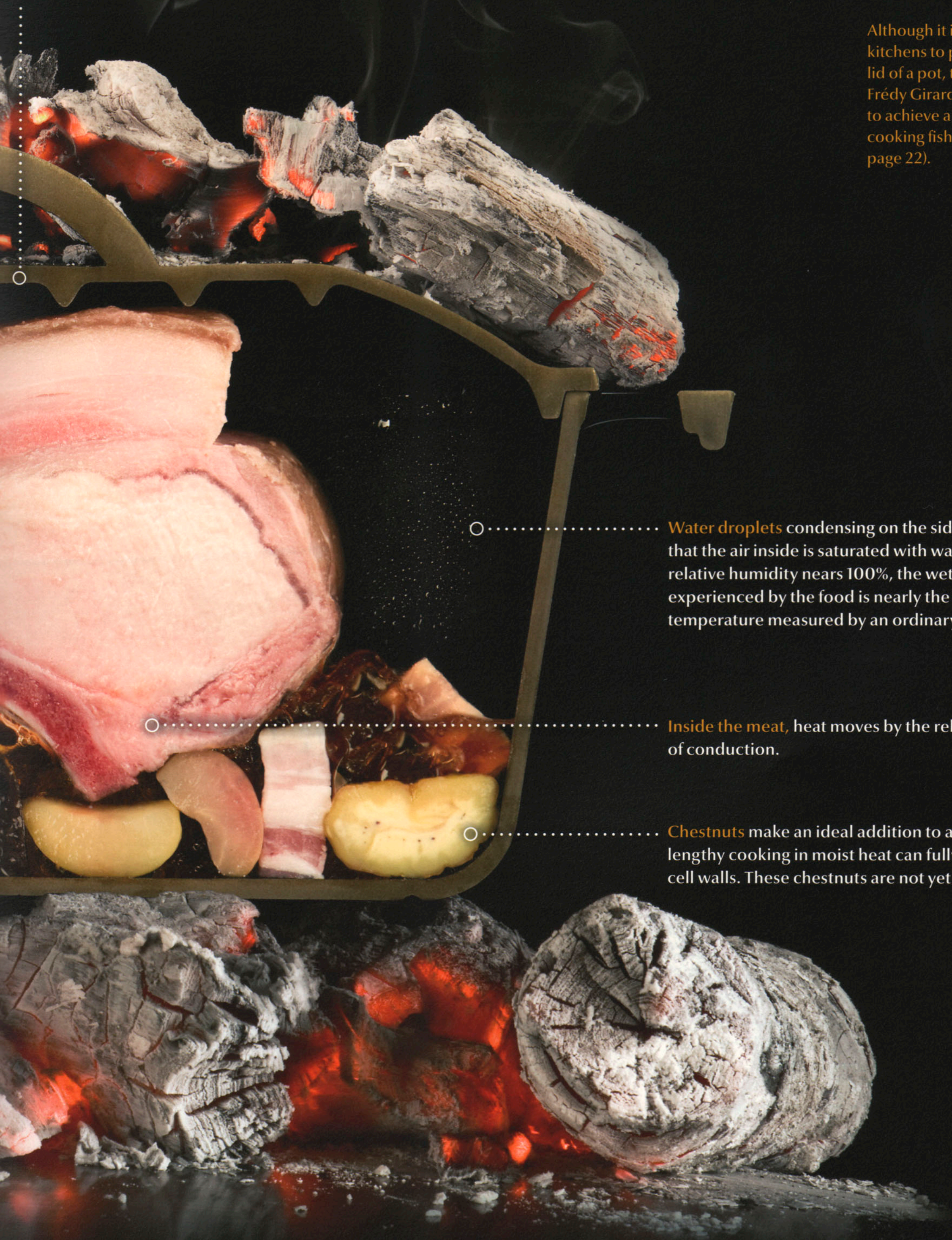
CONVECTION ZONE
Blanketed by humid air, which arises from vaporizing juices, the meat stays juicier. High humidity boosts the rate at which heat moves from the air into the food. It also slows the rate at which water evaporates, which reduces the amount of water drawn out from the interior of the meat.

CONDUCTION ZONE
Gently simmering liquid at the bottom of the pot helps conduct heat directly into the food. The liquid remains, at 77–88 °C / 170–190 °F, just below the boiling point of water. Although a great deal of liquid exudes from the meat and vegetables, most cooks add some additional water or flavorful liquid to quench hot spots that form above the coals and might otherwise scorch the food.

The dull orange glow of the embers indicates a temperature of at least 700 °C / 1,300 °F. A thick layer of ash diffuses the embers' heat across the bottom of the iron pot.

A tight lid is crucial to recreating an authentic pot roast or braise. The lid seals in moisture, which traps flavorful juices, keeps meat moist, and retains heat, so the meat steams rather than stews. The lids of traditional roasting pots had a lip around the edge to help retain embers piled on top; the embers' heat browned the meat below. You can replicate these effects with a modern oven by putting a nonreflective lid—not a shiny one—on the pot and placing it below a hot broiler.

Although it is impractical in most kitchens to place hot coals on the lid of a pot, the great Swiss chef Frédy Girardet invented a way to achieve a similar effect when cooking fish in a broiler (see page 22).



Water droplets condensing on the sides of the pot signal that the air inside is saturated with water vapor. When relative humidity nears 100%, the wet-bulb temperature experienced by the food is nearly the same as the dry-bulb temperature measured by an ordinary thermometer.

Inside the meat, heat moves by the relatively slow process of conduction.

Chestnuts make an ideal addition to a pot roast. Only lengthy cooking in moist heat can fully soften their tough cell walls. These chestnuts are not yet cooked through.

collagen and to convert it to succulent gelatin. The gelatinizing process is critical for tenderizing tough, collagen-rich cuts of meat—the so-called "braising cuts."

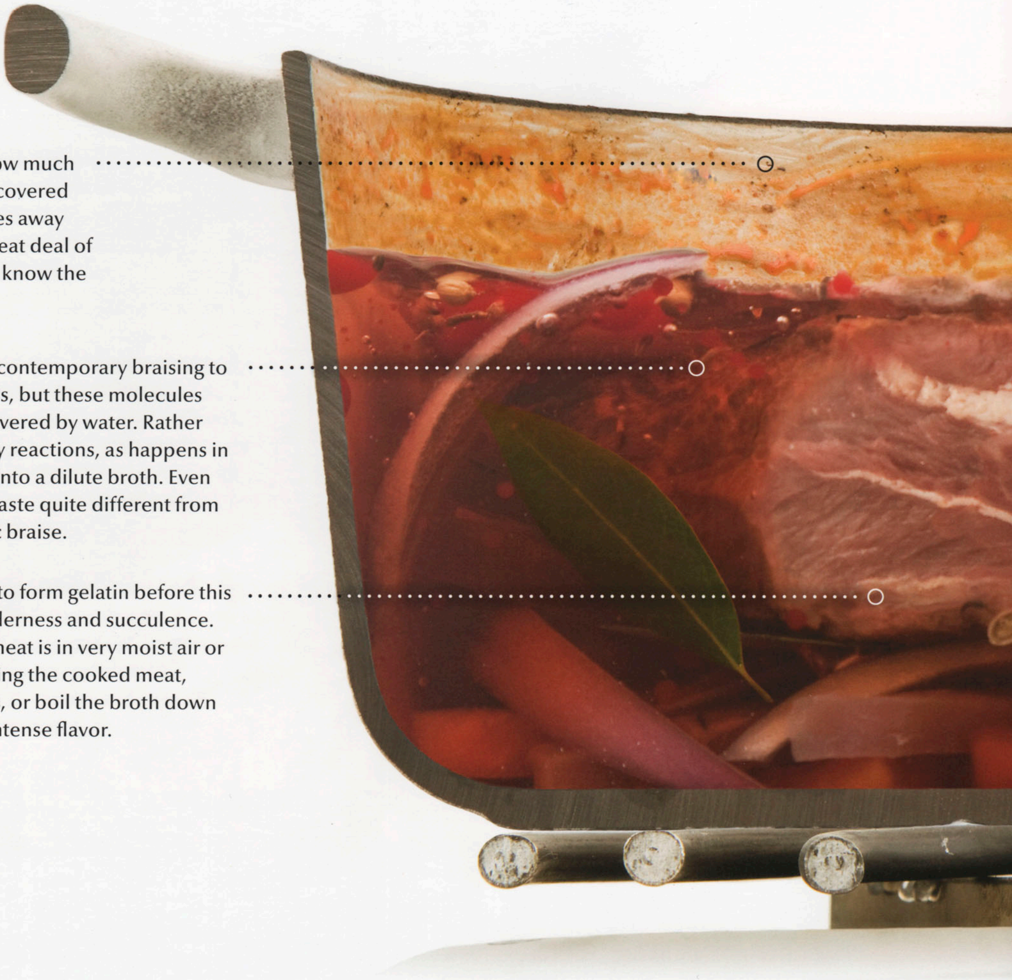
It is worth emphasizing that these various effects occur *only if the pot is covered*. Regardless of whether cooks are using an oven or a stove top, they too often omit the lid during modern braising. That omission can make a dish that could have turned out juicy and tender instead emerge from the pot as dry and tough as boots. Simply adding more liquid to cover the food is no substitute for covering the pot. Although the extra liquid prevents the meat from drying out, it fundamentally changes pot-roasting into a process more akin to stewing.

Water-vapor ovens and combi ovens make it easy to achieve traditional results because they control both the temperature and the humidity. Programmed correctly, these tools can mimic the conditions inside the sealed braising pots used by our culinary ancestors. See chapter 8 on Cooking in Modern Ovens, page 150, for details.

Stewing: Contemporary Braising

The introduction of the oven and the range to the domestic kitchen fundamentally changed the nature of braising and pot-roasting. This technological revolution began in Western Europe and America in the first few years after the First World War. Today, it's easy to forget what a phenomenal transformation this equipment wrought in the way we cook.

For the most part, the changes were for the better. But the adaptations that cooks made to



Residue of liquid lost reveals just how much of a toll evaporation takes on an uncovered pot. The departing steam also carries away volatile aroma compounds and a great deal of heat energy, which makes it hard to know the actual cooking temperature.

Presearing the food is necessary in contemporary braising to create flavorful Maillard compounds, but these molecules readily dissolve when the food is covered by water. Rather than intensifying through secondary reactions, as happens in a traditional pot roast, they diffuse into a dilute broth. Even when boiled down, this liquor will taste quite different from the sauce produced by an authentic braise.

Collagen in the meat must dissolve to form gelatin before this beef check can reach optimum tenderness and succulence. That process works best when the meat is in very moist air or is submerged in liquid. After removing the cooked meat, puree the broth with the vegetables, or boil the broth down to give it greater body and a more intense flavor.

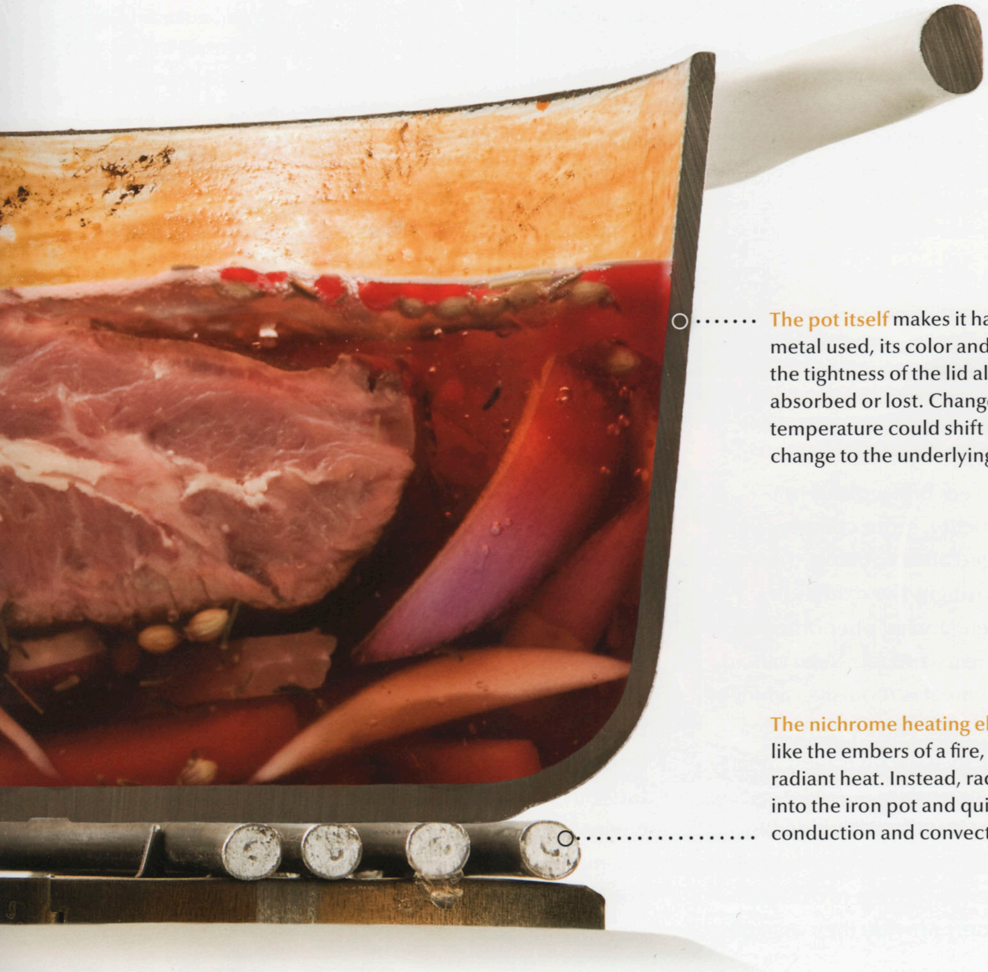
braise and pot-roast in modern ovens or on the stove top were not necessarily improvements. Cooks preparing a braise now typically cover the pot loosely with foil (if at all) before placing it in the oven. The problem with this approach is that ovens are ventilated, so the moisture quickly evaporates from the pot, taking with it many of the volatile molecules that give traditional pot roast its distinctive, enticing aromas and flavors.

If the pot lacks a tight seal, the air inside will never become saturated with moisture. Any portion of the food not submerged in liquid will thus be cooled by evaporation to the wet-bulb temperature, which is significantly cooler than the dry-bulb temperature of the air in the oven. Consistent cooking is nearly impossible in such a situation.

Evaporation through leaky lids is just one of several phenomena that interact to make modern braising so complex and confusing to cooks. Many other factors come into play as well. For example, what color is the pan? Black pans are generally a bit hotter than shiny metal pans because they absorb more radiative heat. What is the balance between the heat lost through evaporation and the heat entering the pot from the oven or burner? That balance depends on the size and the shape of the pot, as well as on how full it is (which changes as the liquid level drops with cooking).

More important still is the humidity of the air in the kitchen. The temperature actually experienced by food braising at a given oven setting can easily vary by 10 °C / 18 °F from one day to the next as the relative humidity changes and accelerates or slows evaporation. If your braising recipe doesn't turn out well, the fault may lie neither with

For more on the crucial role of wet-bulb temperature in cooking, see The Real Baking Temperature, page 103.



The pot itself makes it hard to achieve consistent results. The metal used, its color and shape, the fullness of the pot, and the tightness of the lid all influence the rate at which heat is absorbed or lost. Change any of these, and the actual braising temperature could shift as much as 20 °C / 36 °F without any change to the underlying burner setting or oven temperature.

The nichrome heating element emits invisible infrared rays like the embers of a fire, but it does not cook the food with radiant heat. Instead, radiant energy from the burner flows into the iron pot and quickly moves to the liquid through conduction and convection.

the cookbook nor the cook: variations in these factors may simply have conspired to produce the unfortunate result.

One of the more common forms of failure in braising is meat that turns out less tender and succulent than hoped. Evaporation is again usually the culprit here. Most meats contain more than enough water to dissolve the tough collagen inside them into tender, succulent gelatin. If too much of that natural liquid wicks to the surface and vaporizes, however, the meat dries out, and less of the collagen dissolves.

To avoid such disappointing results, cooks tend to overcompensate by adding so much liquid to the braising pot that the meat is all but submerged. Drowning the meat certainly solves the collagen problem, but it also transforms braising into stewing.

To be clear: stews can be delicious. But stewed foods taste nothing like braised foods. The reason the two techniques produce such a large difference in flavors is that the pool of liquid surrounding a stew shunts the flavor-generating reactions in a different direction than the bit of liquid used for braising does. A different set of aromas prevails as a result.

Then there is the sauce. Overhydrating the food dilutes the cooking liquor so much that it becomes insipid in comparison with the rich concentrate that accompanied traditionally braised or pot-roasted food. A common workaround is to remove the food from the pot and boil the sauce down. Although this approach does concentrate the liquid, consider the price: many of the most aromatic and flavorful elements of the sauce vaporize from the dish and into the kitchen.

Browning poses another challenge for modern methods of braising. To reproduce the effects of the gentle glow of infrared radiation from the coal-covered lid of a traditional pot roast, cooks today brown the meat and some of the vegetables in a hot pan before they add any liquid. Although this approach is eminently reasonable, it also generates a subtly different flavor profile than a traditional braise does. Quick browning generates plenty of Maillard reaction products, but if these molecules then dissolve in a large volume of liquid, they are not as likely to react with one another to produce second-generation flavor compounds as they would be if they were more concentrated. A traditional braise, in contrast, concentrates Maillard compounds in a much smaller volume of liquid at the bottom of the pot, encouraging the creation of more complex and nuanced flavors.

Cooks are increasingly turning to sous vide cooking as a modern alternative to braising because sous vide offers far greater control of the braise.

THE CHEMISTRY OF

Aging Braises and Pot Roasts

As many epicureans have observed, braised and pot-roasted meats often develop a richer, more complex flavor if they have been cooled and aged after cooking, then later reheated for service. Surprisingly, the oxidation reactions that cause this flavor-enhancing phenomenon are similar to those that cause meats and fats to go rancid. Although too much oxidation in meat is repulsive, a hint of slowly oxidized aromatic compounds can be quite pleasant. Indeed, these flavors are partly what give aged meats and cheeses their particular flavor profile.

Interestingly, some of the herbs traditionally added to braises and pot roasts, such as thyme and rosemary, contain powerful antioxidants that moderate the rate of oxidation. Used well, these herbs thus not only provide their own pleasant aromatic qualities but also help to achieve the right amount of aged flavor. Vitamin C, added either as purified ascorbic acid or as an extract of rose hips, can play a similar role. The vitamin is a powerful antioxidant that adds a pleasantly tart taste.

Cooks who use sous vide techniques—which are designed specifically to keep oxygen *away* from the food—face an obvious challenge when trying to achieve results similar to those of aged braising. The simplest workaround is to open the sous vide bag after cooking to allow the food to age for a while. The bag can then be resealed to prevent rancidity and to simplify later reheating. Use caution with this workaround, however, because pathogens can enter the bag while it is open.

HOW TO Braise or Pot-Roast Meat

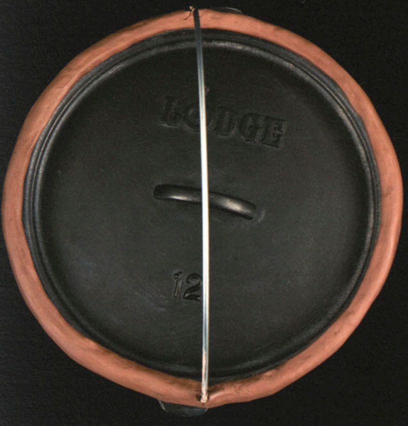
For consistently great braised meat, the most important step is to cover the braise tightly to stop evaporation. As a side benefit, cooking will then occur more quickly because evaporation will not cool the food as it cooks. A snug cover also prevents the meat from drying out.

One trick for mimicking the traditional technique of putting hot coals on the lid is heating a metal lid under the broiler. The lid must get enough heat to enable it to slowly brown the surface of the braising meat below. This trick will enhance the rich, meaty flavor of the braise and its juices.

Cut the meat into large pieces. Whether you are braising or pot-roasting, keep the meat in the largest pieces that will fit comfortably in the pot. The larger the piece, the less surface area through which juices can escape.

2 **Brown the meat.** Use high heat with enough oil for fast and even heat transfer.

3 **Add other ingredients.** If you add liquid, do not add so much that you cover the meat.



4 **Cover with a tight-fitting lid, and cook over low heat.** Use a black lid, which will absorb heat well. To ensure a tight seal, you can cover the rim of the lidded pot with dough or kaolin clay. Cook under a broiler, if available, on an upper rack that places the lid close to the broiler element. Use the lowest broiler setting to simulate the effects of coals piled on top of the lid.

BAKING

A loaf of bread baking … a leg of lamb roasting … the words are so enticing, you can almost smell them. In kitchen parlance, the verbs *to bake* and *to roast* have similar, yet not exactly synonymous, meaning. We unthinkingly choose one over the other to connote subtle distinctions: a baker bakes, for example, whereas a cook roasts. We'd never switch the verbs to describe bread roasting or lamb baking—but why not? Both happen in an oven, after all.

Although today the choice of whether to label oven-cooked food as baked or roasted comes down to little more than advertising, it was not always this way. The origins of the two words reveal how the cooking methods used to differ.

The word *roast* was born around the same time as the English language itself, when the French-speaking Normans defeated the Old English-speaking Saxons at the Battle of Hastings in 1066. Conquest combined the Saxon word *rōstian,* meaning grate or gridiron, with the Old French word *rostir,* meaning to cook before a fire. *Roast* thus originally meant to cook food (held to some form of scaffolding) by the radiant heat of a fire (see Roasting, page 28). Most cooks today find ovens more convenient than fires. So most foods we casually refer to as roasted—roast beef, for example, or roast turkey—are actually baked.

Bake, interestingly, means something quite different from what most people think. The heritage of the word has been traced back thousands of years to *bhōg,* a word in the truly ancient tongue from which, linguists believe, most European and Indian languages evolved. *Bhōg* evolved into the Germanic word *baka,* which became *bacan* in Saxon, then finally *bake* in English. *Bhōg, baka, bacan* all meant the same thing: drying something out by warming it inside of an oven.

But what our Neolithic ancestors were *bhogging* in their ovens wasn't bread. It was bricks! Ovens were invented more than 5,000 years ago for drying mud bricks—and baking them in an oven proved to be a much faster and more reliable method than laying them out in the sun. Baking allowed construction to keep pace with population growth, and oven-dried bricks literally became cornerstones of burgeoning towns and cities—indeed, of civilization itself.

Inevitably, some clever people had the idea to put food rather than bricks into their ovens. But given that ovens were seen as drying machines, they probably didn't bake the food to cook it. In early agrarian societies, after all, most food wasn't eaten fresh—like bricks, it was sun-dried to keep it from rotting. Most likely, early bakers used their ovens to dry their food faster.

And that is still mostly what oven baking does to food: it dries it. So any cook who wants to understand baking—how it really works, why it's harder than it looks, and how to achieve consistent results—needs to comes to grips with the single most important factor in baking: humidity.

Invariably, we describe oven-cooked meat as roasted when, in reality, it is baked. The traditional baked ham is the linguistic exception that proves the rule.

It's Not the Heat; It's the Humidity

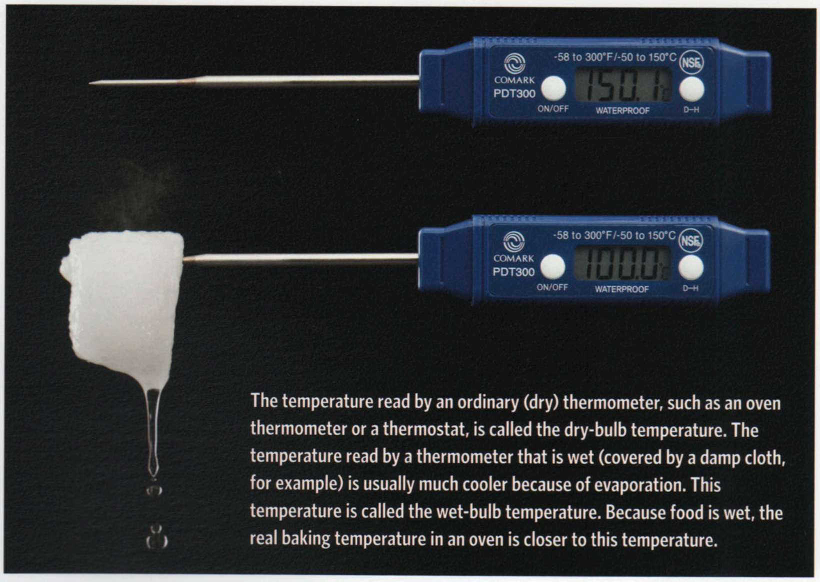
Anyone who has ever overcooked (or undercooked) anything in an oven knows that baking is capricious. Through experience we learn the idiosyncrasies and quirks of our oven, and soon we come to loathe baking in unfamiliar ovens. We can blame the oven—and to be sure it is a deeply flawed technology—but more often than not, our own assumptions are at fault.

You can stick your arm in a hot oven without being burned only because air transfers heat only weakly. Touch the fast-conducting metal walls of a hot oven, and you're sure to get a burn.

Most of us think that baking is just a way to heat something. But that's only half the story. As the oven transfers heat to the food, moisture from the food evaporates into the air as water vapor. Eventually the water vapor disappears out the vent, but before it does it wreaks havoc on the effective temperature of the oven. It is *the* primary cause of erratic results. Compared with this, the other concerns about baking are such small details that in most cases they are simply irrelevant.

Although heating elements and burners are extremely hot, they're relatively small. They are no match for the rush of cold air that occurs when you open your oven door. The walls of an oven provide a much bigger surface area from which to supply heat. That's why preheating is so important: hot oven walls help maintain a steady baking temperature. This is especially true of wood-fired ovens, which usually have thick masonry walls to hold the heat.

Water vapor is so important because it, much more than the thermostat setting you dial in, determines the actual cooking temperature. In other words, it's not the heat; it's the humidity. Humidity inside a conventional oven, unfortunately, is largely under the control of the food, not the cook. That's why turning the control knob on your oven is a bit like spinning a roulette wheel—you never know exactly where the cooking temperature (which, as we'll explain, is very different from the temperature measured by your oven thermometer) will end up. Worse still, it will almost invariably change, perhaps dramatically, during the three distinct stages of drying that occur during baking.



The temperature read by an ordinary (dry) thermometer, such as an oven thermometer or a thermostat, is called the dry-bulb temperature. The temperature read by a thermometer that is wet (covered by a damp cloth, for example) is usually much cooler because of evaporation. This temperature is called the wet-bulb temperature. Because food is wet, the real baking temperature in an oven is closer to this temperature.

Why Preheat?

The only time during baking that cooks actually have full control over the temperature inside their oven is when the oven has finished preheating, before the food goes in. Preheating is important because it gives the oven a large and reasonably well-controlled reservoir of heat energy to draw on as it reacts to the influx of cold that occurs when food is inserted. Preheating is one simple way to stack the odds in favor of consistent baking.

Preheating always seems to take an unreasonably long time. Why? The short answer is that most of the hot air is wasted. The actual energy required to reach the baking temperature is quite small; just 42 kJ will heat 0.14 m^3 / 5 ft^3 of air to 250 °C / 480 °F. The heating element in a typical oven supplies this much energy in a mere 21 seconds.

It is the oven walls you want to preheat, however, not the air. Unfortunately, the heat must pass through the air to get to the walls, and air is a truly awful conductor of heat, only slightly better than Styrofoam insulation (see How Heat Conducts Itself, page 1·277). Even worse, air is a wasteful medium because, being a gas, air expands when heated (see When Hot Particles Move, page 1·279). The hotter the air, the more it expands, and much of it simply spills out the vent to heat the kitchen rather than the oven. Closing the vent is not an option because without an avenue for escape the expanding air could cause the oven to pressurize and eventually explode.

Skipping the preheating step is not a good option either. If you put food into the oven as soon as the air inside is hot but before the walls are at the target temperature, the cold food will warm only a little before the air loses most of its excess heat. Exacerbating the situation, the warming food will emit water vapor, a cool, dense gas. The water vapor will sink to the bottom of the oven, forcing hotter, less dense, dry air up and out the oven's vent.

Now the oven has to heat this mixture of cooler air and water vapor. And of course they too

THE PHYSICS OF

Why Baste Food?

Basting food is a lot like deep-frying it a bit at a time. Whether you're baking in an oven or frying over a burner, dribbling food with hot fat or oil will speed cooking in a couple of ways. First, a coating of oil puts a lid on evaporation, raising the wet-bulb temperature—and therefore the effective cooking temperature—at the surface of the food. The coating of oil can also be much hotter than the boiling point of water, so any water droplets the oil encounters at the food surface flash to steam and erupt through the oil as jets of vapor. These constant eruptions stir the cooler air that surrounds the food, and the resulting turbulence increases the rate of heat transfer—just as convection currents in a deep fryer do.

Taken together, these two effects heat and dry the food surface more quickly and evenly than either baking or panfrying alone. The result is often a crisp and delicious crust—the very best incentive for basting.

expand when heated, needlessly throwing away still more heat. All of this puts a strain on an oven's heating element or burner, and baking slows.

As soon as you open the oven door to adjust or check on the food, all of the hot air and vapor spills out. The puny electric element or gas burner in most ovens is sized for the steady state situation, so it is no match for such large surges of cool air. The temperature in the oven plummets and recovers only slowly.

Preheating the massive walls of the oven helps prevent such excursions in temperature. The hot walls can store large quantities of heat energy and can release it quickly when needed to rapidly restore the temperature inside.

The Real Baking Temperature

When you preheat your oven, you dial in a desired baking temperature. This is called the **dry-bulb temperature**. It sets the stage for the first phase of baking. There's more going on in this phase than most people realize.

As hot, dry air flows over cool, wet food, the temperature at the surface of the food begins to rise steadily. Moisture is always evaporating from the surface of food, of course, but the evaporation accelerates as the dry-bulb temperature rises.

Because it takes energy to change water from liquid to vapor form, the evaporation cools the food as it dries it. That cooling effect slows the rise in the surface temperature of the food.

So at the same time that hot air in the oven is adding heat to the food, evaporative cooling is sucking heat out of the food. The two processes are in competition. Which one will win?

The surprising answer is that, for most of the baking time, evaporation wins in nearly all foods. Until the surface of the food is almost completely dried, evaporation holds the exterior temperature of the food to below the boiling point of water. The oven may be set to 250 °C / 480 °F, but as far as the food is concerned, the cooking temperature is at least 150 °C / 270 °F cooler than that.

What's happening is that all of the additional heat energy arriving at the surface of the food is being used to vaporize water rather than to increase the temperature of the food. Simply put, none of the heat sinks in. During this phase of baking, the effective baking temperature becomes stuck at something less than 100 °C / 212 °F—usually a lot less—at the **wet-bulb temperature**, which is defined as the temperature of evaporating water. Because the wet-bulb temperature is defined by the temperature of evaporating water, it cannot ever be above 100 °C / 212 °F.

You can't really master baking until you understand that the wet-bulb temperature is the real baking temperature, the one that determines how fast the turkey, leg of lamb, or loaf of bread will take to bake. Even though the wet-bulb temperature is more important than the dry-bulb temperature, it is less familiar to cooks.

The two temperatures differ in several critical ways. The wet-bulb temperature can never be hotter than the dry-bulb temperature. It can also never be hotter than the boiling point of water. The dry-bulb temperature is independent of humidity, but the wet-bulb temperature rises dramatically as the relative humidity of the

For more on the surprising amount of heat energy consumed by evaporation, see The Energy of Changing States, page 1·300.

THE TRADITIONAL BAKED TURKEY

Much of the conventional thinking about an oven-cooked turkey is off the mark. People invariably refer to a bird cooked this way as "roasted" when in fact any food cooked in an oven is baked. We focus too much attention on how the meat heats, even though how the food dries in the oven is at least as important. And while many cooks assume that the skin will soon reach whatever temperature they set the oven to, that feeling of control is an illusion. The invisible hand that actually controls the baking temperature of food in an oven is the humidity that arises from water evaporating from the food.

Oven thermostat: 205 °C / 400 °F
Dry-bulb temperature: 205 °C / 400 °F
Wet-bulb temperature: 98 °C / 208 °F
Relative humidity: 4.5%

BOUNDARY LAYER
Humid air tends to stagnate just above the surface of food. Natural convection slowly mixes drier surrounding air into this layer and propels the drying process. Forced convection does the same thing more forcefully, thus accelerating drying.

DESICCATION ZONE
Once the skin and meat just below dry out, their temperature begins to rise above the boiling point. But it never actually reaches the dry-bulb temperature at which the oven thermostat is set. Heat moves through this region mainly by conduction, aided by a small amount of convection from steam entering the air.

BOILING ZONE
When the heat and humidity in the oven are high enough, water will boil in a very narrow region beneath the surface of the food. Here, heat also moves almost entirely via conduction. Flowing juices carry a small amount of heat by convection.

CONDUCTION ZONE
In most of the food, heat travels by conduction only. Capillary flow does carry some water outward very slowly near the surface.

Oven walls act as a reservoir of heat that keeps the air temperature steady. But they also emit radiant heat that can cause uneven browning.

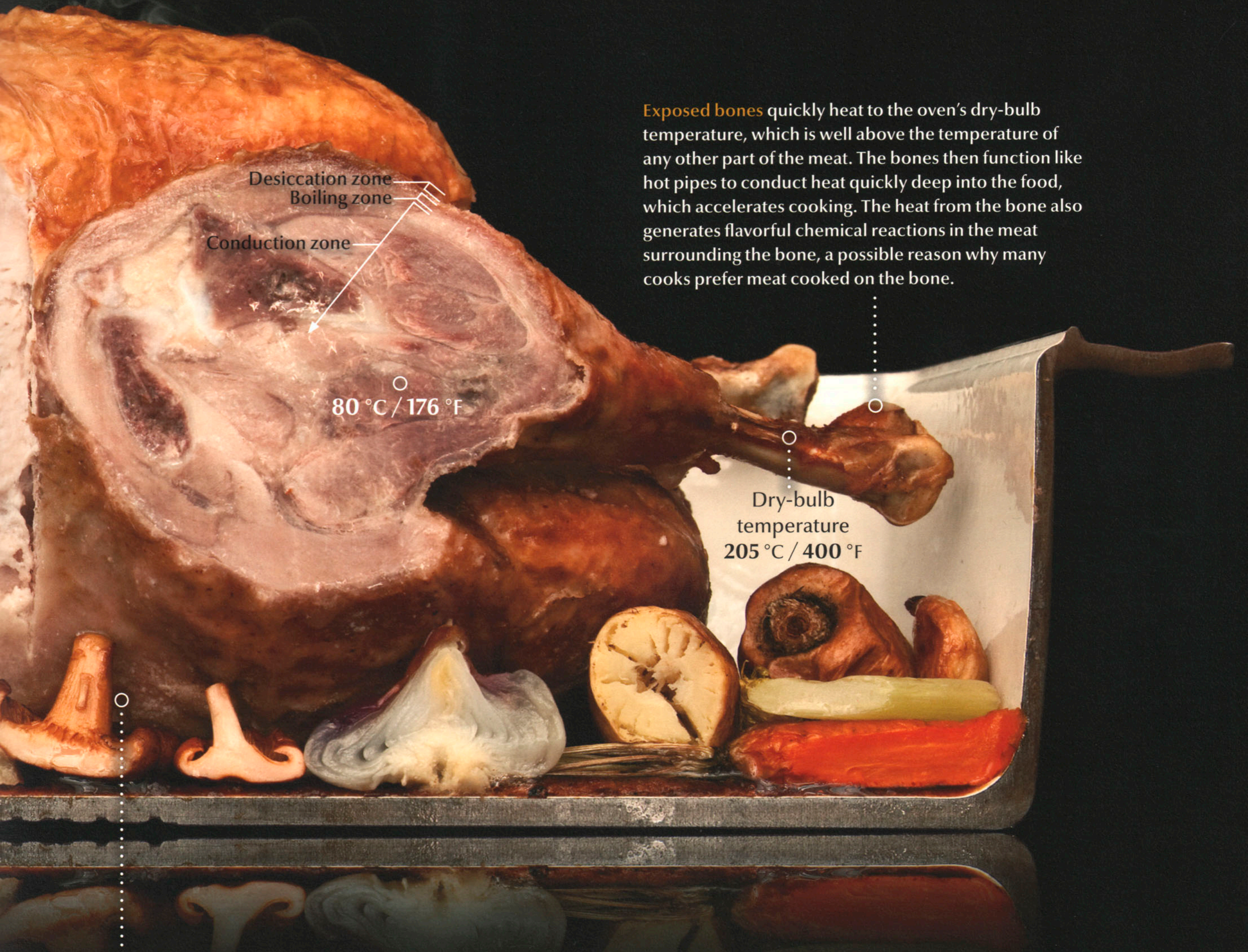
A roasting tray or baking sheet can make for soggy meat. Although the metal conducts heat to the surface of the food faster than air can, it captures pools of liquid that quench the temperature to no higher than the boiling point of water.

As moisture evaporates from the desiccation zone, juices slowly wick up from below, pushed by diffusion and pulled by capillary forces. The trickle of juices provides a continual supply of sugars, peptides, and oils that chemically rearrange to create the characteristic color, tastes, and aromas of baking food.

Convecting air and radiation from the oven walls heat the outside of the food. Water at the surface vaporizes, raising the humidity in the oven.

THE MYTH OF RESTING

Many books on cooking have claimed that high cooking temperatures force water towards the center of the food, and that resting allows the water to move back from its hiding place. This is not true. Water moves outward near the surface of the food to replace water lost through evaporation. Deeper within the food, water does not move at all. The water does, however, break free from other components in the food at a molecular level. That is why food fresh from the oven will leak juices when sliced. Resting food helps prevent these leaks by slightly thickening the juices as they cool. For a more complete description of the phenomenon, see What Happens When Meat Rests, page 3·84.



Exposed bones quickly heat to the oven's dry-bulb temperature, which is well above the temperature of any other part of the meat. The bones then function like hot pipes to conduct heat quickly deep into the food, which accelerates cooking. The heat from the bone also generates flavorful chemical reactions in the meat surrounding the bone, a possible reason why many cooks prefer meat cooked on the bone.

Food submerged beneath the liquid won't brown or crisp. For better results, use a roasting rack to hold food above the liquid.

Relative humidity measures the capacity of air to accept water vapor. When it is at 100%, the air cannot accept more water vapor, and condensation occurs. The absolute amount of water that air can hold changes strongly with the dry-bulb temperature. Relative humidity readings are always specific to a given temperature. For more details, see page 1·314.

When the dry-bulb temperature exceeds the boiling point of water, relative humidity becomes undefined because the air can then accept an unlimited amount of water vapor.

Food baking in an oven dries out in three distinct stages (shown from left to right): the settling period, the constant-rate period, and the falling-rate period. For many foods, like tomatoes drying in a warm oven, the last stage can take a long time because, once the exterior of the food has dried completely, moisture can escape only slowly.

surrounding air increases. Wet-bulb temperature is the dry-bulb temperature minus any cooling by evaporation. The lower the relative humidity, the more evaporative cooling, so the bigger the difference between the two temperatures.

In the extreme case—100% relative humidity, when the hot oven air cannot hold another drop of water vapor—the wet-bulb temperature will equal the dry-bulb temperature. Because the wet-bulb temperature can never exceed the boiling point, such high humidity can occur only at dry-bulb temperatures below the boiling point of water.

Unfortunately, the wet-bulb temperature is difficult if not impossible to control in a traditional oven. You can adjust the dry-bulb temperature just by twisting a knob, but there is no comparable control for the wet-bulb temperature, except in expensive combi ovens and water-vapor ovens (see Cooking with Moist Air, page 154).

You can measure the wet-bulb temperature directly by wrapping the bulb of an oven thermometer in a wet cloth (but be sure to allow it time to warm up and settle, and keep the cloth damp). Or you can try to predict it by looking up the dry-bulb temperature, the humidity in the oven, and the current air pressure on a psychrometric chart (see How to Measure Relative Humidity, page 1·322). But neither of these methods is particularly easy.

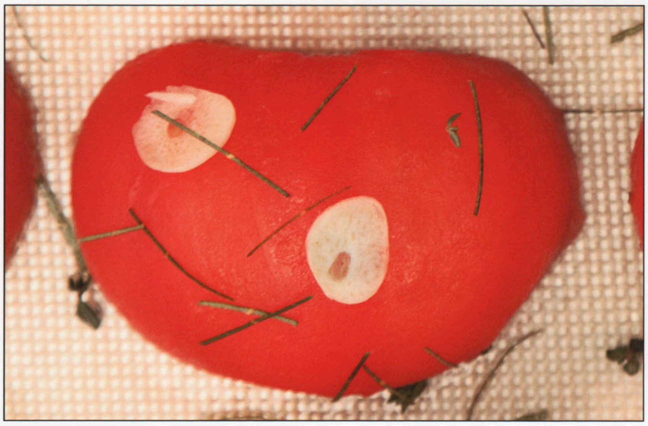
Unknown and uncontrolled, the wet-bulb temperature is the biggest source of inconsistency when baking. This fact is why water-vapor ovens, combi ovens, and sous vide water baths produce much more consistent results than traditional ovens do. Each of these modern technologies provides some measure of direct control of the elusive wet-bulb temperature. If you're baking with a traditional oven, you will need to focus instead on managing the three stages of drying.

The Stages of Drying

Baking, we've now established, is all about drying. It's helpful to think of drying as occurring in three distinct stages. In the first, called the **settling period,** the temperature at the surface of the food quickly rises from its starting point up to the wet-bulb temperature but then stalls and remains at a plateau until the surface dries substantially.

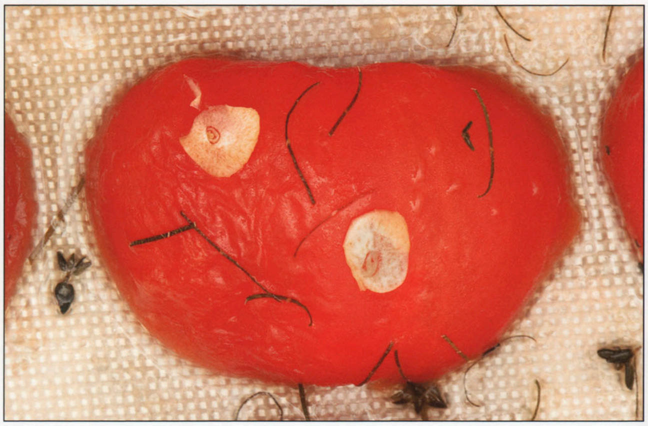
After the initial settling period, the wet-bulb temperature increases again but more slowly than before. When enough water evaporates from the food, the humidity in the oven increases appreciably. The jump in humidity retards further evaporation and frees the wet-bulb temperature to inch upward.

Next comes the **constant-rate period,** when evaporation flings water from the food into the air,



Dry-bulb temperature: 60 °C / 140 °F
Surface temperature of tomatoes: 40 °C / 104 °F
Wet-bulb temperature: 40 °C / 104 °F
Relative humidity of the oven: 30%

In the settling period, the fruit quickly heats and soon settles at the wet-bulb temperature.



Dry-bulb temperature: 60 °C / 140 °F
Surface temperature of tomatoes: 50 °C / 122 °F
Wet-bulb temperature: 50 °C / 122 °F
Relative humidity of the oven: 58%

Both the wet-bulb temperature and the relative humidity in the oven rise during the constant-rate period as water evaporates from the food. The surface of the food looks and feels wet during this stage.

but water is just as quickly replenished by capillary action and diffusion, which drive juices to the surface from deeper within the moist interior. During the constant-rate period, the core gradually begins to dry, and its temperature rises to equal the wet-bulb temperature in the oven.

There is a yin and a yang to this effect. Often, when we bake something, we want it cooked *and* juicy, so we want the constant-rate period to be as brief as possible. Cooking with a high dry-bulb temperature, with high humidity—or, even better, with both—helps curtail this stage.

Other kinds of foods, however, are baked primarily to dry them out. In such cases we want to extend the constant-rate period to allow enough time for the slow processes of capillary action and diffusion to remove water from deep within the food. Baking with dry air and a low dry-bulb temperature (below the boiling point of water) aids dehydration while preventing the outside from burning.

The third and final stage of drying, called the **falling-rate period,** begins once the surface of the food becomes desiccated. Evaporation has raced ahead of capillary action and diffusion, so juices from the center no longer reach the surface to keep it wet. Now a delicious crust forms in the desiccation zone. Beneath the crust, however, the food is still moist, and evaporation continues there. What happens next depends on whether the dry-bulb temperature is above or below the boiling point of water.

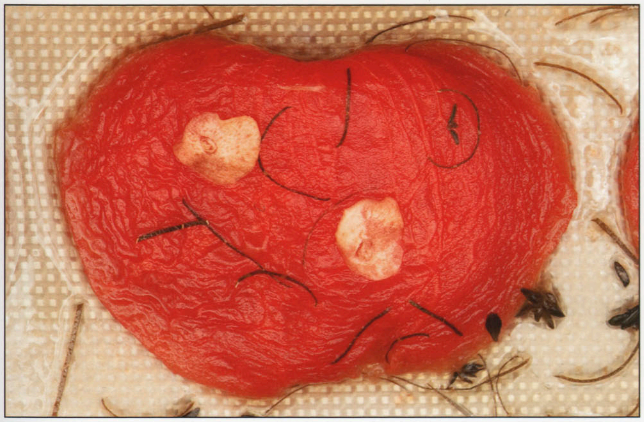
At dry-bulb temperatures below 100 °C / 212 °F, the real baking temperature of the dry crust, as well as that of a narrow layer of still-moist food just beneath it, shoots up quickly to nearly match the oven temperature. The sudden rise occurs because evaporation slows. The dry crust thickens and traps water below it. Much of that confined water is tightly bound to the molecules of the food, so it cannot evaporate readily. As evaporation dwindles, so does its cooling effect.

Things work a little differently when the dry-bulb temperature in the oven is above 100 °C / 212 °F, as is typical for baking. Once a dry crust appears on the food, a boiling zone forms beneath that crust. The food in that region cannot get any hotter than the boiling point of water until nearly all the water there evaporates.

Boiling does accelerate cooking because it conducts heat into the core as fast as possible. But for delicate meats and seafood this comes at a steep price: overcooking of a large proportion of the interior. At this stage of baking, if you're not careful, you can easily boil the food to death.

On the other hand, the same hot oven does wonders for the crust. As the crust heats up to the dry-bulb temperature of the oven air, it undergoes

Whether you set your oven to 100 °C / 212 °F or hotter, the real baking temperature will quickly rise higher than the wet-bulb temperature at some point in the falling-rate period. If you are directly measuring the wet-bulb temperature in your oven, take care not to inadvertently overcook the food during this phase.



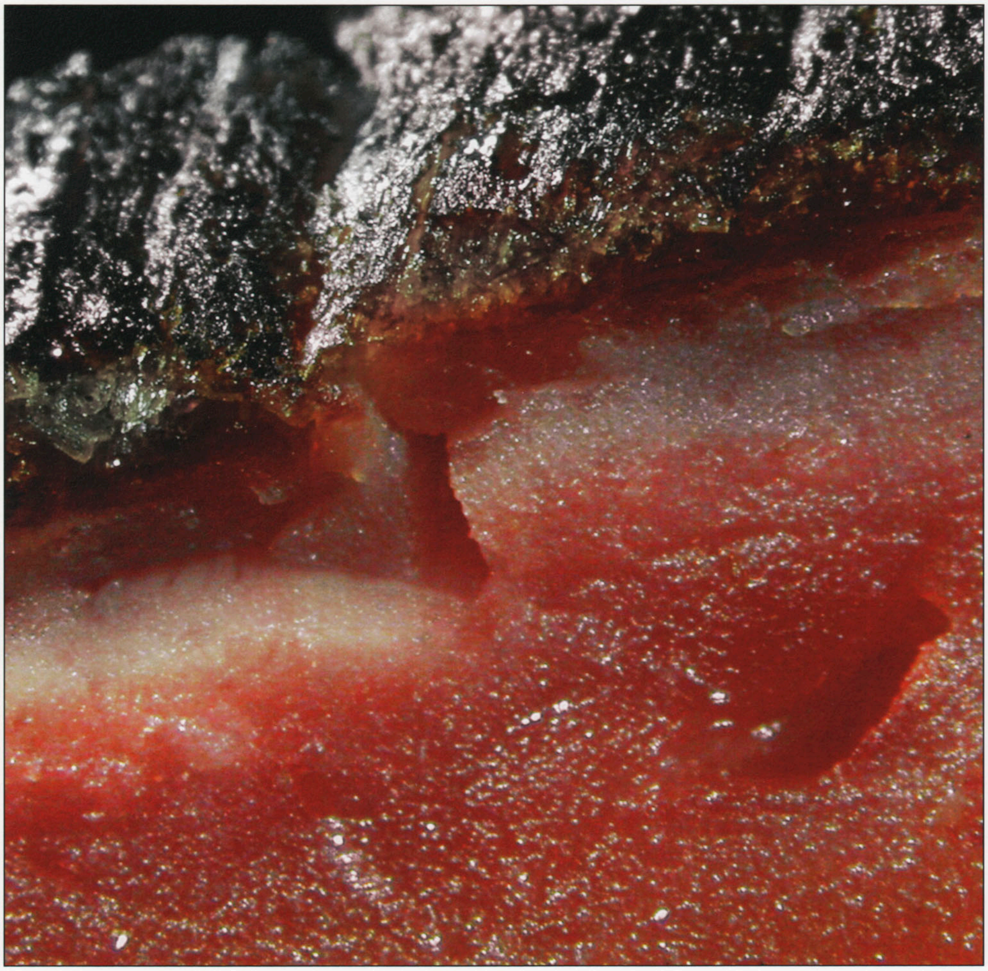
Dry-bulb temperature: 60 °C / 140 °F
Surface temperature of tomatoes: 54 °C / 129 °F
Wet-bulb temperature: 50 °C / 122 °F
Relative humidity of the oven: 58%

In the falling-rate period, evaporation slows, and the tomatoes become tacky and eventually dry to the touch. With less evaporation to cool the food, the surface temperature rises above the wet-bulb temperature.

Dry-bulb temperature: 60 °C / 140 °F
Surface temperature of tomatoes: 59 °C / 138 °F
Wet-bulb temperature: 40 °C / 104 °F
Relative humidity of the oven: 30%

Once drying is complete, both the humidity and the wet-bulb temperature fall inside the oven. It can take a long time for moist foods to reach this point. Resist the temptation to accelerate the process by turning up the temperature; that can harden the surface and trap water inside, thereby causing uneven drying.

A CLOSER LOOK AT THE BAKING CRUST



A thin boundary layer of stagnant air surrounds parts of the exterior surface of this baking beef rib roast and slows both its absorption of heat and its evaporation of water.

The crust that forms in the desiccation zone allows heat to move into the food both by convection of water vapor and by direct conduction where the meat contacts the "roasting" pan.

In the boiling zone beneath the crust and dried-out meat, the temperature is exactly at the boiling point of water. This temperature is the real baking temperature of the meat.

Most of the meat is in the conduction zone, where temperatures are below boiling and heat conducts slowly toward the core.

As food dries during baking, its true baking temperature changes depending on how quickly water is evaporating from beneath the surface. Thus, the best way to measure the real baking temperature is by sticking the tip of your thermometer into the zone slightly beneath the dry surface of the food.

a cascade of complex chemical reactions that usually include the Maillard reaction. The resulting pigments paint a golden hue across the crust of everything from baking bread to "roasting" meat.

These chemical changes happen quickly at temperatures above 130 °C / 265 °F. So a typical baking temperature of 205 °C / 400 °F would burn the crust were it not for wafts of steam and a trickle of juices continually percolating up from the boiling zone. Together, they provide just enough moisture to cool the browning surface long enough for baking to finish. They also provide a steady supply of chemical ingredients—dissolved sugars, proteins, oils, and other reactive molecules—for the flavorful reactions occurring at the crust that make baking, well, baking.

Convection Baking

So far we have focused on how heat moves from the surface crust (the desiccation zone) through the boiling zone (where evaporation dominates) and into the conduction zone as it makes its way toward the center of the food. But we haven't yet discussed where the heat comes from: a fourth, invisible zone between the air and baking food. This region, called the **boundary layer,** is important in baking because it controls how fast convection can heat the surface. If you want to understand where a convection oven excels and where it doesn't, you need to know what happens in the boundary layer.

Drag is one important thing that happens there. Any time a fluid (such as air) passes over a surface,

THE SCIENCE OF

Why "Beer Can Chicken" Really Does Work

Some chefs may turn up their noses at the "beer can chicken" technique popularized by tailgaters, but it's actually a fantastic way to cook a chicken. Baking a great "oven-roasted" chicken always involves the dilemma of how to get both tender, juicy meat *and* golden, crispy skin.

The problem is that skin needs to cook at surprisingly high temperatures to dry and brown (see Cooking Skin and Innards, page 3·116), whereas the flesh is at its best when cooked at much lower temperatures. Some poultry desecration, an empty beer can, and a two-step baking process solve the dilemma.

The steps below include the essential step of flaying the skin, which makes it into a kind of balloon that inflates away from the wet flesh. The skin thus dries before the meat overcooks. Even after the bird comes out of the oven, steam continues to emerge and hold the crisped skin apart enough to stay crispy for longer than your typical "roast" chicken does.

With the chicken upright on a can, juices can drain away, so they don't accumulate and make the skin soggy. The standing position also lets air reach and dry all of the skin, including the back, which crisps up better than any other part of the bird.

HOW TO Roast Chicken on a Beer Can

The steps below will work in any oven. For photos of many of these steps, see How To Roast Chicken in a Combi Oven, page 178, which presents an approach specific to that kind of oven that goes even further in search of the perfect golden bird.

1 **Preheat oven to 80 °C / 175 °F (or the lowest setting your oven allows).**

2 **Separate the skin from the meat (see photos on page 178).** Starting from either the neck or the cavity opening, work your fingers under the skin and pull it away from the flesh. Move your fingers down the thighs, legs, and around the back of the chicken, taking care not to tear the skin. When you've finished, the skin should hang loosely on the bird, attached only at the wings and the very tips of the drumsticks.

3 **Use the tip of a knife to make a hole in the skin at the bottom of the legs and along the chicken butt so that juices can drain.**

4 **Empty a beer can (this is the fun part), and insert the can into the cavity of the bird.** Adjust the can so the chicken will rest upright on it.

5 **Bake the chicken to a core temperature of 60–65 °C / 140–150 °F, about 3–4 h for a bird of average size.** If you prefer juicy and tender white meat, we recommend the lower temperature; use the higher temperature if you favor succulent dark meat. Monitor the effective baking temperature by using a digital thermometer pushed about 1 cm / ⅜ in beneath the skin. If the temperature rises more than a couple of degrees above your target, open the oven door to lower the temperature and humidity for a few minutes. Conversely, increase the oven's temperature slightly if the desired final temperature hasn't been reached at this depth after 30 min of baking.

6 **Remove the bird from the oven when done, and set it aside uncovered.**

7 **Turn the oven to its highest setting and preheat for 20 min.**

8 **Return the chicken to the oven, and bake until the skin is golden and crispy.** Use forced convection if your oven has that feature. Watch the bird closely; this step goes fast, and a moment's inattention is all it takes to burn the bird.

9 **Remove the crispy chicken from the oven, carve, and serve.**

drag slows it down. The deceleration can be so pronounced that small, thin puddles of stagnant air constantly pool over parts of the food surface. The dead air in these puddles acts like a wet blanket: it makes it hard for heat to get into the food and harder for water vapor to get out.

The boundary layer is thicker in a still oven than it is in a convection oven with the fan going, and it is thicker around rough foods than it is around slippery surfaces. In general, the faster and more easily the air slides over the food, the thinner the boundary layer and the faster that heat transfer and evaporation can occur.

So it stands to reason that baking should happen faster in a convection oven, where a powerful fan continuously stirs the air around the food. Convection baking is faster, but often only slightly. The dramatic reductions in cooking time frequently touted for convection ovens are the exception rather than the rule. What's more, forced convection does not actually make baking more even, as many people seem to think.

When the fan in the oven blows, it strips away water vapor near the surface of the food and mixes it with drier surrounding air. The boundary layer thins, and the exterior dries faster than it otherwise would. So forcing convection does not directly speed cooking; it's more accurate to say it speeds drying.

Exposed to a steady supply of dry air, the evaporation zone recedes into the food where, if the oven is hot enough, it becomes a boiling zone that drives heat conduction toward the core. A hot oven and a powerful fan can force the boiling zone deeper into the food than natural convection would. It is an indirect process, but the end result is that baking finishes faster.

How much faster varies greatly from one kind of food to the next, however. Thin food (such as bacon) benefits the most. Baking times shrink far less for thick foods (such as a ham) because the faster drying caused by forced convection makes the exterior crust thicker—an effect that is sometimes but not always desirable. Once that crust thickens, which happens more readily on dry foods, it behaves like a heat shield. The boiling zone recedes deep inside the food, and faster convection at the surface has little further effect on heating or evaporation.

The conventional wisdom that a forced-convection oven "cooks 25% faster" or "10 degrees hotter" than a conventional oven is thus so oversimplified as to be a fallacy. The actual difference in cooking time depends on what part of the cooking process is the limiting factor that determines the baking time. In large foods, the time it takes to conduct heat into the core controls cooking speed; a convection oven doesn't appreciably accelerate that. In thinner foods, conduction is a smaller part of the overall process, and the convection oven can make a bigger difference. There is no simple rule that applies in all cases.

Baking bacon finishes faster in a forced convection oven, as do other thin foods that need to be dried as much as they need to be heated. For thicker foods, convection baking saves much less cooking time. Unfortunately, there are no hard and fast rules about how much quicker the cooking goes.

Scorched by Heat Rays

Forced convection cannot completely solve the problem of uneven baking because the air is not the only source of scorched spots—radiant heat is.

The hot walls of an oven are always radiating infrared energy. The hotter the oven temperature, the more intense the infrared radiation bouncing around inside it. You can't see this, but you can certainly feel it. Stick an arm into an oven set to 120 °C / 250 °F, and it will feel warm. But try this in an oven set to 290 °C / 550 °F, and it will feel intensely hot right away. The fact that you can feel the difference immediately is a clue that it's not the air providing the heat you feel.

Unfortunately, oven walls always radiate heat unevenly. The walls are thicker in some spots than in others, and some parts of the wall are closer to the burners or heating elements than others. So the temperature can fluctuate by tens of degrees from one spot to another. Many oven doors contain a window, which radiates a lot less heat than the walls do.

At low oven temperatures, these fluctuations don't matter much because radiant heat is weak; but, at high baking temperatures, they matter a lot. The power of radiant heat emitted from part of an oven wall at 270 °C / 520 °F is 16% more intense than the power coming from part of a wall that is slightly cooler at 250 °C / 480 °F.

Exacerbating this problem, the food itself also absorbs radiant heat unevenly. Some parts of the surface naturally dry faster and brown earlier. Because dark surfaces absorb more radiant heat than light surfaces do, these small variations are quickly magnified by radiant heat. If the oven is hot enough, or if a darkening part of the food is

particularly close to an intense spot of radiant heat, those parts of the food are likely to scorch and burn. Far from solving these problems, forced convection ovens can actually make things worse because they accelerate the uneven drying that contributes to uneven browning.

Ultimately, there is little to be done about this aspect of baking. Beyond using a shiny oven or baking at low temperatures, a baker can only keep his oven clean (see note at right) and pay attention to how the food is browning. Rotate the food as needed, and consider shielding problematic spots on the food with aluminum foil to reflect incoming radiant heat.

Why Consistency Is So Elusive

Your single most powerful tool for achieving consistent results—not only when baking but when using all of the cooking techniques in this chapter—is accurate temperature control. At the most fundamental level, temperature is what determines whether food is underdone, overdone, or done just right.

The challenge is that baking involves two temperatures, dry-bulb and wet-bulb, and we can control only the dry-bulb temperature. As for the wet-bulb temperature, we can only strive to be aware of it, to measure and monitor it, and to develop some intuition about the factors that affect it (see The Real Baking Temperature, page 103).

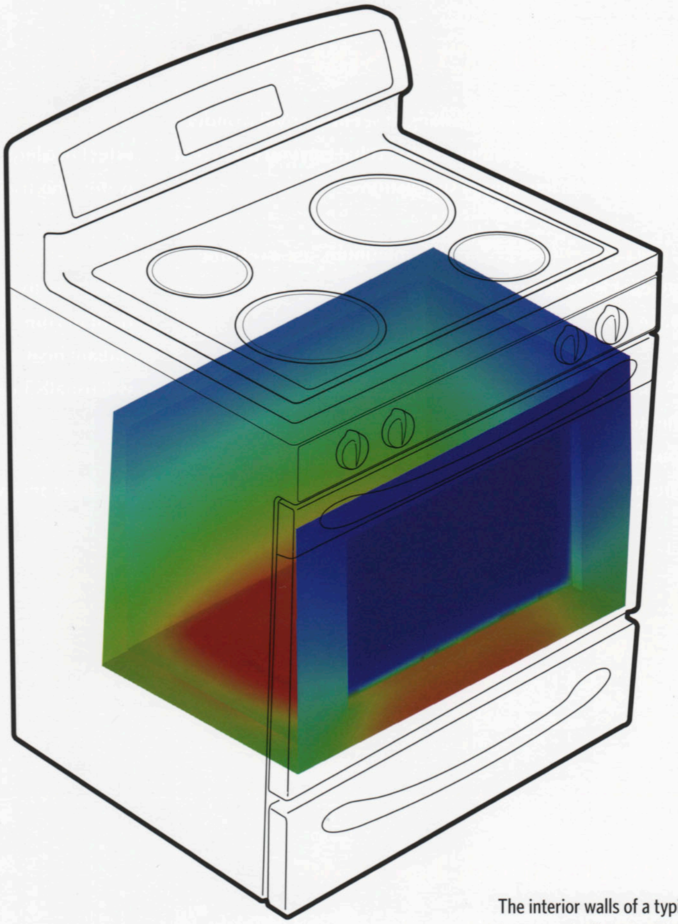
Controlling temperature would be easier were it not for two more frustrating facts about ovens that conspire against consistency. First, the thermostat in nearly all traditional ovens is just plain wrong. As technologies go, it is underwhelming: it is nothing more than a switch that opens and closes in response to the temperature it senses. In the worst case, the sensing probe is located behind the oven walls. In the best case, it protrudes into the oven cavity. (It's a metal tube with a crimped end.) Inside, it is filled with an incompressible fluid that responds to changes in temperature just like an alcohol-filled glass thermometer.

This type of temperature sensor mismeasures the real dry-bulb temperature by as much as 14 °C / 25 °F at high baking temperatures, and often by even more at very low temperatures. The more physical distance between the sensor and the food, the bigger the error. You can and should calibrate the dry-bulb thermostat of your oven for more consistent baking.

The second frustrating fact about ovens is that bigger batches bake faster. You already know that a lightly loaded oven will heat differently than an oven that has food on every rack. But you might subscribe to the conventional wisdom that a fully loaded oven will take longer to bake. In actuality, however, as long as an oven is properly preheated, a full oven will usually bake food faster than one that is largely empty.

The reason is that humidity increases the real baking temperature, and most of the humidity in an oven comes from the food itself. A single sheet of cookies will not increase the humidity in the oven to saturation, but a full load of cookies will, and it will do it fast.

This situation means that proper cooking times can vary for different batch sizes. Keep that in mind when you are developing a recipe for a small volume and scaling it up.



The interior walls of a typical oven have hot spots (red) and cold spots (blue) that make it difficult to bake food evenly. Any grease stains on the walls will burn to a dark black and become hot spots because darker surfaces are more efficient emitters of radiant heat. So keep your oven clean. Some modern ovens have mirror-like interiors that emit very little radiant heat. In principle, this should reduce fluctuations in temperature between one part of the oven and another.

STRATEGIES FOR CONSISTENT BAKING

Given all of the factors that influence baking, it seems a small wonder that any cook ever achieves consistent results. What can you do to rein in the variation? We have a few simple suggestions.

Calibrate the thermostat of your oven. At a minimum, use a reliable thermometer to check the temperature of the oven in the center, where the food will bake.

Know the real baking temperature. Monitor it by probing a thermometer just beneath the surface of the food. Pay attention to water vapor. If the wet-bulb temperature gets too high, lower the oven's dry-bulb temperature with the thermostat, or open the oven door to lower the humidity.

Bake in consistent batch sizes. If that's not possible, then simulate the effect of a larger batch by filling unused shelves with open pans of water. This trick will not produce identical results, but it will help.

Pay attention to browned spots. Move the food around as often as necessary to keep hot spots of radiant heat from scorching the food. The door of your oven, especially if it has a glass window, will emit the least radiant heat of all the oven walls. The back of your oven near the corners will usually be the hottest part.

Consider getting a modern oven. Many are designed to control the dry-bulb and wet-bulb temperatures accurately—see chapter 8.

Batch size has a dramatic effect on baking times. After 20 min of baking at 180 °C / 355 °F, a fully loaded oven has a wet-bulb temperature of 99 °C / 210 °F, a moderately loaded oven has a wet-bulb temperature of 88 °C / 190 °F, and a lightly loaded oven has an effective baking temperature of a mere 65 °C / 150 °F. That's why, contrary to what you might think, a fully loaded oven often bakes food faster.

THE IMPORTANCE OF

Location, Location, Location

How is New York City different from Mexico City? Altitude, for one. Most cooks know that elevation affects boiling or canning food because it changes the boiling point of water. But the same physics also changes an oven's wet-bulb temperature. Take a look at how that happens in two cities with twin ovens.

Initially, the oven in New York has a higher wet-bulb temperature because there is more water vapor in the oven to begin with. Air at sea level can hold more water than air at a high altitude, even when both have the same relative humidity.

The oven in Mexico City catches up after just 17.5 s of baking, and it maintains its advantage for another 18 min by as much a 5 °C / 9 °F. The evaporation rate is always faster at high altitude because there is less atmospheric pressure to resist evaporation

The boiling point of water drops with elevation, however, and the wet-bulb temperature can never be hotter than the boiling point of water, so the New York oven gets hotter in the end.

After 1 h of baking, the oven in New York bakes 4 °C / 7 °F hotter. After 3 h, it bakes 6 °C / 11 °F hotter. So much for the simple rule that an oven at higher altitude always bakes at a cooler temperature. Sometimes yes, sometimes no: it just depends on the cooking time.

Further Reading

Textbooks on Traditional Cooking

Campbell, J., Foskett, D. *Advanced Practical Cookery: A Textbook for Education & Industry.* Edward Arnold, 2006.

Cook's Illustrated Magazine. *The New Best Recipe.* America's Test Kitchen, 2004.

Culinary Institute of America. *The Professional Chef.* Wiley, 2001.

Ducasse, A. *Grand Livre De Cuisine: Alain Ducasse's Culinary Encyclopedia*. Ducasse Books, 2009.

Gisslen, W. *Professional Cooking.* Wiley, 2010.

Labensky, S. R., et al. *On Cooking: A Textbook of Culinary Fundamentals*. Prentice Hall, 2010.

Lienhard IV, J. H., Lienhard V, J. H. *A Heat Transfer Textbook*. Prentice Hall, 1987.

Montagne, P., editor. *Larousse Gastronomique.* Clarkson Potter, 2001.

Pepin, J., Perer, L. *Jacques Pepin's Complete Techniques*. Black Dog & Leventhal, 2001.

Peterson, J. *Cooking.* Ten Speed Press, 2007.

Ruhlman, M. *The Elements of Cooking: Translating the Chef's Craft for Every Kitchen*. Scribner, 2010.

Cookbooks for Specific Cuisines or Techniques

Cottenceau, M. *The Professional Charcuterie Series.* Van Nostrand Reinhold, 1991.

Davis, A. A., Kirk, P. *The Kansas City Barbeque Society Cookbook*. Andrews McMeel, 2010.

Girardet, F. *Girardet: Recipes from a Master of French Cuisine*. Ten Speed Press, 2004.

Kutas, R. *Great Sausage Recipes and Meat Curing.* Stackpole Books, 2007.

Mallmann, F., Kaminsky, P. *Seven Fires: Grilling the Argentine Way*. Artisan, 2009.

Peterson, J. *Sauces: Classical and Contemporary Sauce Making.* Wiley, 2008.

Ruhlman, M., Polcyn, B. *Charcuterie: The Craft of Salting, Smoking, and Curing.* W. W. Norton, 2005.

Sokolov, R. *The Saucier's Apprentice: A Modern Guide to Classic French Sauces for the Home.* Alfred A. Knopf, 1976.

Tsuji, S., Tsuji, Y. *Japanese Cooking: A Simple Art.* Kodansha International, 2007.

Walsh, R. *Legends of Texas Barbecue Cookbook: Recipes and Recollections from the Pit Bosses.* Chronicle Books, 2002.

Willingham, J. *John Willingham's World Champion Bar-B-Q: Over 150 Recipes and Tall Tales For Authentic, Braggin' Rights, Real Southern Bar-B-Q and All the Fixin's.* William Morrow Cookbooks, 1996.

Young, G., Richardson, A. *The Breath of a Wok: Unlocking the Spirit of Chinese Wok Cooking Through Recipes*. Simon & Schuster, 2004.

The Science of Cooking

Adrià, F. *Modern Gastronomy: A to Z*. CRC Press, 2009.

Barham, P. *The Science of Cooking.* Springer, 2001.

Corriher, S. O. *CookWise: The Secrets of Cooking Revealed*. William Morrow Cookbooks, 1997.

Joachim, D., et al. *The Science of Good Food: The Ultimate Reference on How Cooking Works.* Robert Rose, 2008.

McGee, H. *On Food and Cooking: The Science and Lore of the Kitchen*. Scribner, 2004.

This, H. *Kitchen Mysteries: Revealing the Science of Cooking.* Columbia University Press, 2007.

This, H. *The Science of the Oven*. Columbia University Press, 2009.

Wolke, R. L. *What Einstein Told His Cook: Kitchen Science Explained*. W. W. Norton, 2008.

Wolke, R. L., Parrish, M. *What Einstein Told His Cook 2: The Sequel: Further Adventures in Kitchen Science*. W. W. Norton, 2005.

Reference and Technical Books

Davidson, A., Jaine, T. *The Oxford Companion to Food*. Oxford University Press, 2006.

Fellows, P.J. *Food Processing Technology: Principles and Practice*. CRC Press, 2009.

Incropera, F., et al. *Introduction to Heat Transfer.* Wiley, 2006.

7

COOKING IN OIL

The technique of cooking in oil is cloaked in kitchen myth and culinary lore. Many people believe that deep-fried food is inherently greasy and unhealthful, for example. But it doesn't have to be: the simple act of blotting French fries straight from the fryer can drastically reduce the amount of fat they contain.

At the opposite extreme are those who have unwavering faith in the seemingly magical ability of molten animal fat to transform a boring cut of meat into a superbly rich confit. In fact the making of a confit is far from mystical, and other cooking methods can honorably substitute for the ritual cauldron of fat.

To dispel some of the mystery surrounding these subjects, we will examine the forces at work when food encounters hot oil. The physical mechanisms of deep-frying, shallow frying, and confit cooking actually require only a superficial explanation. We mean this literally: in each of these of techniques, the oil affects only the surface of the food. Below the surface, heat is just heat; the food responds no differently than it would if it were baked in air or boiled in water.

But saying that cooking in oil is superficial is not at all the same as saying that oil is unimportant. Quite the opposite—whereas air and water are simply fluids that we cook in, oil is much more: not only a cooking medium, but also an ingredient. Heat cooks oil just as it does most other ingredients, and the way that oil changes during heating has a profound impact on whether the food cooked in it will be appealing or appalling.

Will the oil impart a pleasant flavor and give the food a warm and slippery mouthfeel? Or will the oil leave the food rancid-tasting, scorched, and unpleasantly greasy? The answer depends on the kind of oil used and how skillfully it is handled, alone or with the other ingredients in the fryer.

Amazingly, the bubbles erupting from frying potatoes (left and above) are filled with nothing but water—in the form of steam. They signal the profound importance of water vapor in deep-frying. Even submerged in hot oil, food encounters a humid environment as water vaporizes from the food surface. The bubbles stir cooler oil near the food into the hotter surrounding oil, much as forced convection stirs the air in an oven.

For a comparison of the heat-transfer rates of various methods of cooking, see It Matters How You Heat, page 1·283.

For more on the importance of wet-bulb temperature in cooking, see It's Not the Heat; It's the Humidity, page 102.

Just Like Baking, Only Faster

Deep-frying works a lot like baking. In both techniques, a convecting fluid transfers heat to food: the oil in a deep fryer churns in response to differences in buoyancy between hot and cold layers, just as the air in an oven does. The same distinct cooking zones form while baking and frying food, and humidity plays a major role in the cooking temperature during deep-frying as well.

Humidity? Yes, indeed. It may seem that food submerged in hot oil should not be subject to the effects of humid air, but it is. The moisture comes from water in the food that is driven to evaporate by the heat applied to the food surface. This effect is invisible in baking, but in deep-frying the water vapor gives rise to countless steam bubbles that form in the oil around the food (see illustration on page 124).

Steam does emerge from the food less readily in oil than it does in air. Oil puts a lid on evaporation: it contains the water vapor coming from the food at least momentarily. The pockets of steam that envelop the food raise the humidity and therefore the wet-bulb temperature, which remains the effective cooking temperature as long as the surface of the food is wet.

The temperature of the oil serves as the dry-bulb temperature, like the temperature of the oven thermostat during baking. (Although oil doesn't seem all that dry, the point is that oil doesn't have any water in it.) The moisture-trapping ability of oil brings wet-bulb and dry-bulb temperatures closer together in deep-frying than they typically are in baking.

Preheating an oven is crucial to baking, and you want to preheat your frying oil for the same reason: to absorb the cold shock that occurs when food is added, so that each batch of food cooks consistently. Typical preheating temperatures, which range from 150–200 °C / 300–390 °F, are lower than those used for high-temperature baking because the oil will erupt into flames if it gets too near its smoke point. You wouldn't want to cook in oil hotter than 200 °C / 390 °F anyway because the high rate of heat transfer during frying would probably cause the outside of the food to burn before the inside cooks.

A last crucial connection of deep-frying to baking is the division of the cooking process into three distinct stages: the settling period, the constant-rate period, and the falling-rate period. The duration of each stage is much shorter when frying than when baking, however, so the process demands greater vigilance.

Once food enters the hot oil, things happen fast. Swirling currents of oil heat the surface of the food to the wet-bulb temperature in only a few seconds—a rushed version of the settling period that occurs during baking (see photos on page 106). As long as bubbles are streaming from the food, you can be sure that the surface is wet and thus no hotter than boiling water. The cooking temperature at the food surface will remain a constant 100 °C / 212 °F as long as juices percolate from the

Potato chips and fried chicken are both deep-fried, but they have different textures because of their different sizes. Thin foods cook through evenly, so chips can be crispy on the inside as well as the surface. Large, thick foods cook more quickly at the surface than at the center, so you can get a moist, tender interior and a crispy or crunchy crust.

moist interior to the surface of the food at least as fast as water evaporates from the food surface.

The settling period may be over in an instant, or it may last a few minutes. It will take longer for larger or thicker pieces of food, for food coated in wet batter, and for foods in which the juices don't flow readily to the surface.

During this phase of cooking, the jets of steam bubbles stir and thus shrink the stagnant boundary layer that insulates the food from the oil. The Jacuzzi-like action thus moves heat from the oil to the food faster—often two or three times faster than occurs once the bubbles have stopped emerging. But as with forced convection in an oven, faster heat transfer during deep-frying simply accelerates drying.

Pay close attention when the streams of bubbles start to slow: a mere trickle indicates that the surface is drying and that a crust is forming. The food is nearly through the constant-rate period now and is approaching the final stage of deep-frying, when it could easily burn. On irregularly shaped food, some parts could burn even while other parts are still bubbling.

At the end of deep-frying, during the falling-rate period, the temperature of the crust rises quickly, and the boiling zone moves deeper into the food, just as they do in the final stage of baking. This is the point at which the golden color and crispy or crunchy crust develop, the *raisons d'être* of deep-frying.

This last stage also presents the principle challenge of deep-frying, which is to cook the food to the center before the crust burns. Although the same challenge must be faced during baking, deep-frying is much less forgiving of imperfect timing because oil moves heat much faster than air does.

Sized Just Right

Circulating hot oil transfers heat extremely rapidly, so deep-frying is one of the fastest ways to cook the surface of food. Beneath the surface, however, heat propagates in frying food in the same way it does in any other cooking technique: slowly, through conduction. The mismatch between a fast-cooking surface and a slow-cooking interior means that food needs to be sized just right for deep-frying.

Intuitively, cooks know that small or thin pieces of food are better suited for deep-frying than large, thick pieces are. It's possible to make a more exact statement mathematically by calculating a quantity called the **Biot number**. It is the ratio of how readily heat moves from the oil into the surface of the food to the rate of conduction of heat into the center of the food.

In technical terms, the Biot number $Bi = (h \times V) \div (A \times k)$, where h is the heat transfer coefficient of the oil, V is the volume of the food, A is the surface area of the food, and k is the thermal conductivity of the food. Thus, reducing the volume of food while increasing the surface area produces a smaller Biot number and more evenly cooked food.

If this ratio is a very small number—because the food conducts heat very rapidly, is very small or thin, or both—then the center heats nearly as fast as the surface. When you deep-fry food with a low Biot number, you find that it maintains an even temperature from edge to center throughout the cooking process. This is the case with thin fried chips, for example.

If the Biot number is large, on the other hand, the surface becomes a bottleneck through which the heat can pass only slowly. The edges of the food then heat much faster than the center. Unfortunately, this latter situation is the more common experience of cooks who deep-fry.

Food is such a poor heat conductor that anything except paper-thin slices of food heat faster at the surface than at the center. This effect can be something to celebrate. In French fries, for example, it accounts for the exquisite contrast between a crispy crust and a light, fluffy interior.

Jean-Baptiste Biot was a French physicist who made significant contributions to the fields of optics, magnetism, and astronomy in the early 19th century. He was also the first scientist to supply convincing evidence that meteorites came from outer space.

But there's a reason you won't find French fries much larger than your fingers. When foods are too large, uneven heat transfer from the surface to the center becomes a problem. It takes so long to raise the temperature at the center of the food that the intense heat of deep-frying overcooks the outside or, worse, burns it.

When in doubt, cut food into smaller pieces. Small objects have a lower Biot number than large ones; they heat more evenly from surface to center, and they also heat through faster. If you can cut the volume of food in half, you will decrease the cooking time by as much as a factor of four. What's more, you'll avoid the unhappy experience of eating deep-fried food that is burned on the outside and raw in the center.

For more on conduction, see Heat in Motion, page 1·277.

BUBBLE, BUBBLE, OIL, AND ... STEAM?

You've probably heard deep-fried food described as being "submerged in oil." That is not exactly true. If the frying oil is in peak condition, the food will directly contact oil for no more than half the cooking time. The rest of the time, water vapor streams out of the food in bubbles and shoves the oil aside.

The water inside this cauliflower expands 1,600 times in volume as it turns to steam. The water vapor bursts through fissures and pores on the food surface, erupting from steam "volcanoes" into the surrounding oil. The steam bubbles prevent the food from absorbing any oil until after frying is finished. Only then does capillary action wick oil into the vegetable's dry cracks and pores.

Columns of steam erupt from the surface of the food, disrupting the surrounding layer of cool oil and allowing hot oil to rush in.

Steam bubbles also push oil away from the surface of the food, preventing the oil from seeping into the interior.

Until the surface dries, it remains at the wet-bulb temperature, which cannot go above the boiling point of water.

Once dry, the surface heats rapidly toward the temperature of the oil, and starches and sugars in the food caramelize and brown.

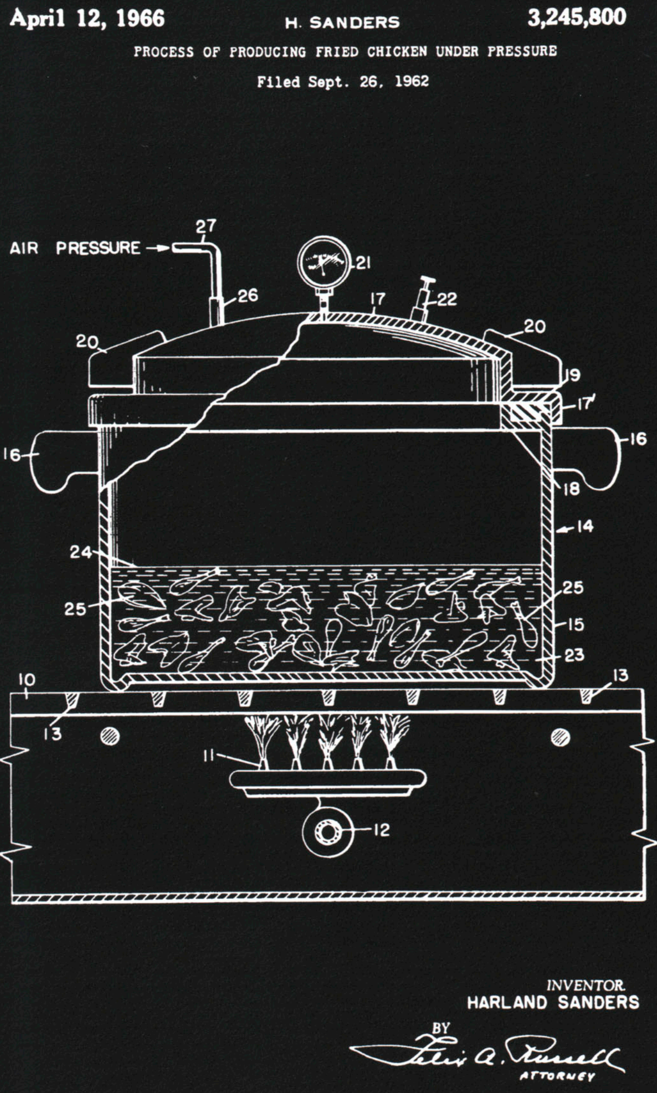
Heat conducts slowly to the interior of the food, despite the high temperature at the surface.

FRYING UNDER PRESSURE

In the 1950s, when Colonel Harland Sanders started the Kentucky Fried Chicken franchise, chickens enjoyed longer lives, and their muscles—particularly their legs—were tougher. Cooking these old birds fast and to order was no mean feat because their dark meat was loaded with tough collagen. The colonel knew that simply turning up the heat on the fryer wouldn't work; higher heat at the food surface just doesn't accelerate cooking appreciably.

So Sanders instead financed the development of a new kind of deep fryer, one that uses high pressure rather than high temperature to speed cooking and tenderize dark meat. Winston Shelton—who later invented the CVap water-vapor oven—came up with the winning design. Winston Industries' "Collectramatic" is still sold today.

But tough chickens and dark meat have gone out of style. Birds are now butchered 10 weeks sooner than they used to be, and the animals have been bred to yield more of the tender but easily overcooked white meat the public seems to prefer. The 21st-century Collectramatic has thus evolved as well to cook at pressures and temperatures considerably lower than those applied in Sanders's day.



April 12, 1966 H. SANDERS 3,245,800

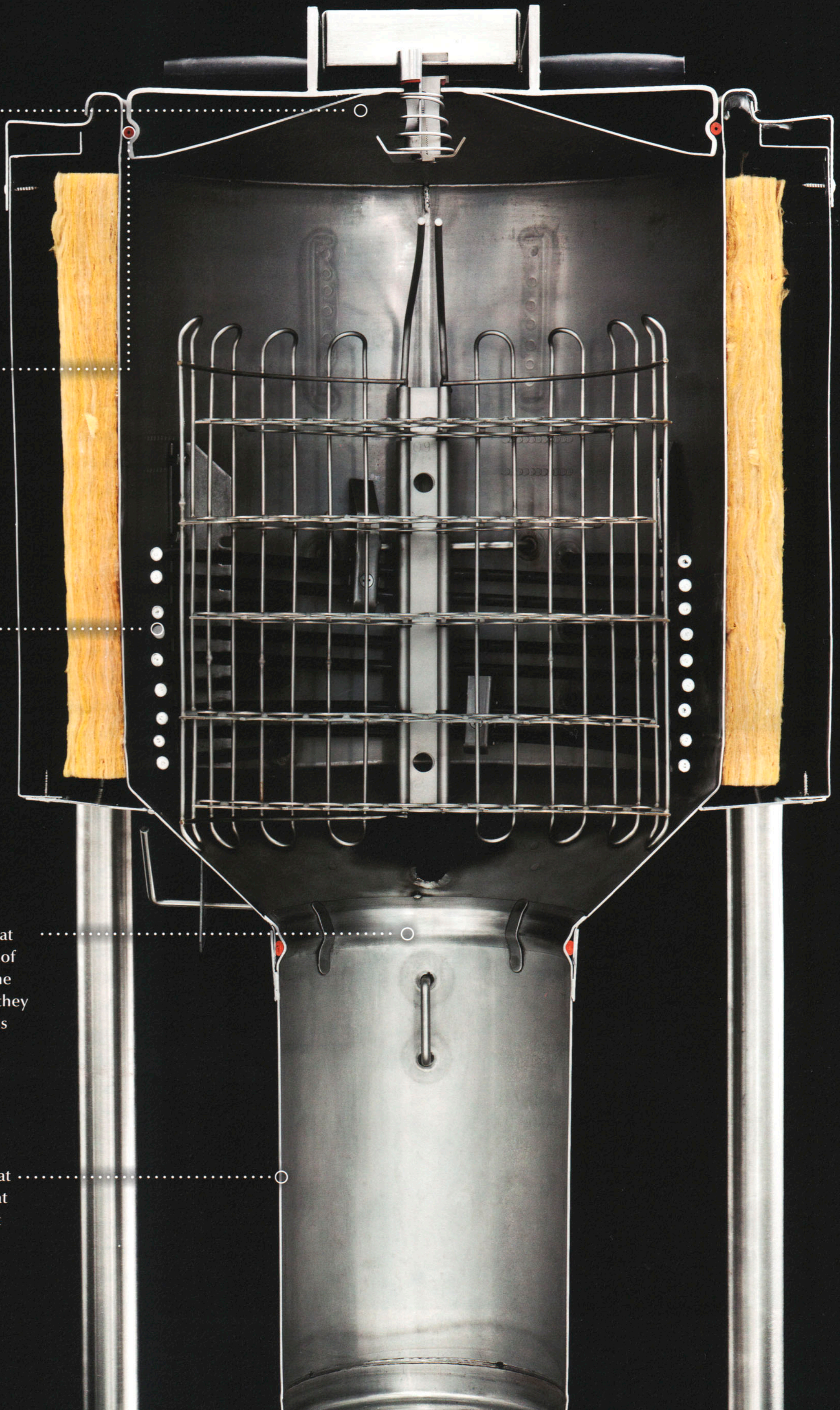
PROCESS OF PRODUCING FRIED CHICKEN UNDER PRESSURE

Filed Sept. 26, 1962

INVENTOR
HARLAND SANDERS
BY
Felix A. Russell
ATTORNEY

The invention that spawned a fast-food empire: Col. Harlan Sanders's 1966 patent for a pressure fryer, descendents of which are still used today in KFC restaurants.

The cooking rack loads all of the pieces of food into the fryer simultaneously so that they all cook for the same amount of time.



Pressurized headspace raises the boiling point of water in the food from 100 °C / 212 °F to 106 °C / 223 °F, reducing the amount of juice that vaporizes from the frying fowl.

The seal contains pressures that are much lower than those used in other kinds of pressure cookers.

Electric heating elements heat the oil to a constant temperature.

The crumb collector (not shown) at the bottom of the fryer holds bits of crackling and batter that fall off the food at low temperatures so that they do not burn, ruining the oil. That is why the heating element is positioned above.

Thin, uninsulated walls ensure that the debris-laden oil that collects at the bottom stays cool and doesn't burn. This keeps the oil in peak condition longer.

For an example of multistage frying, see the recipe for triple-cooked chips, page 3·322.

If you use any of these precooking techniques, be sure, for safety's sake, to blot the moisture off the surface of the food before dropping it into hot oil.

In Pursuit of the Golden Crust

In addition to sizing, you can exploit several other strategies to achieve a perfectly textured, golden crust. Which approach you choose depends in part on the kind of food you're frying.

One simple approach to avoid burning is to turn down the temperature on your fryer. At temperatures from 160–165 °C / 320–330 °F, the Maillard reaction and other chemical reactions that brown a dry crust still occur—albeit a bit more slowly than at higher temperatures—but the food won't burn.

The batter on a piece of halibut (above) and the shell on a prawn (below) serve the same function in deep-frying: to trap water vapor and protect delicate food from the scorching heat of frying oil. Because of these barriers, the food stays moist and cooks at temperatures cooler than that of the oil.

The downside of cooler frying is that the texture of the crust can sometimes suffer. The archetypal thin, pleasantly crispy or crunchy crust is a direct result of the quick drying that happens at high temperatures. Turn down the heat, and the surface of some foods dries more slowly, yielding a thick, hard crust that very often becomes tough and chewy as the food cools.

Lower temperatures aren't always an option. If puffing the food is important, for example, then very hot oil is a must.

A second strategy, which works well for delicate foods that aren't too large, is to coat the food in a wet batter. The coating fries into a superb crust even as it protects the food from overcooking. In the oil, the water in the batter boils steadily, but a pocket of cooler, humid air develops between the batter and the food. The food essentially bakes in this cool zone of moist air rather than frying in the oil.

The thickness of the batter determines just how cool this blanket of air will be. Thin, tempura-like batters have a slight cooling effect, whereas thick, wet batters cool food substantially. Of course, batters have the added virtue of producing the kinds of irresistible crusts that are a hallmark of great deep-frying.

A third strategy that works well with many kinds of food is multistep deep-frying—that is, cooking the food before frying it. For vegetables and other foods that aren't easily overcooked at near-boiling temperatures, you can do both steps in the deep fryer. First, cook the food all the way through at a relatively low temperature, typically 120–140 °C / 250–285 °F. Then remove the food while you raise the temperature of the oil to 180–200 °C / 355–390 °F. When the oil reaches the target temperature, plunge the food back in until a golden-brown crust appears.

A two-stage cooking process can also work well for tender meats and delicate seafood, but only at much lower temperatures. You want to avoid raising the surface of the meat to the boiling point; otherwise, it will overcook long before it browns. Although you could parcook meat or seafood in oil, that seems like a lot of fuss when other gentle, low-temperature cooking techniques will suffice. Low-temperature baking or poaching

The color of potato chips results directly from the temperature at which they are deep-fried. Browning reactions occur relatively slowly at temperatures below 155 °C / 310 °F. Above 170 °C / 340 °F, food will burn if left too long in the oil. Between those extremes, the chips will never get darker than the golden colors shown no matter how long they're cooked.

is a simpler way to parcook before you fry.

The very best strategy for deep-frying tender or delicate foods, however, is to precook the food sous vide. Sous vide cooking affords tight control over cooking temperature, time, and humidity, so it almost always yields superior results with foods that demand accurate cooking. And you can use sous vide to avoid chopping because you can ensure that large pieces of food have cooked through before you dunk them in the deep fryer to develop a delicious crust.

Oil Changes

Oil is the most important ingredient in deep-frying. It affects the flavor of the food, how well it browns, how quickly it cooks, how greasy it becomes, and how healthful it is to eat. Yet cooks rarely give much thought to oil once it's poured into the vat of a deep fryer. They neglect to consider that food isn't the only thing cooking in there: the oil is too!

Heating oil to high temperatures initiates a cascade of chemical reactions that have a profound effect on flavor (see The Secret Life of Frying Oil, next page). First the fat molecules oxidize, forming highly reactive peroxide molecules. Then these unstable peroxides interact with other molecules in the oil to produce a menagerie of compounds with varying flavors. Many are wonderfully aromatic; they impart the characteristic aroma of deep-frying to the oil and, hence, to the deep-fried food. Others smell awful and can be unhealthful as well as unappetizing.

The proportion of pleasant to unpleasant compounds in oil depends in large part on how much frying the oil has done. Most cooks recognize that old, heavily used frying oil will make the food cooked in it taste rancid. Not as many know that fresh oil has limitations, too.

Straight from the can or bottle, most frying oil is practically odorless and tasteless because the chemical reactions that produce flavorful compounds haven't been completed yet. Food cooked in fresh oil also browns less quickly and evenly. But why should that be, given that fresh oil gets just as hot as oil that has been broken in?

The answer comes down to the simple fact that oil and water don't mix—at least not at first. Steam bubbles streaming from deep-frying food push away the surrounding oil, so the food actually isn't in constant contact with it (see Bubble, Bubble, Oil, and … Steam?, page 118). In fact, food frying in fresh oil spends as little as one-tenth of the cooking time in contact with the hot oil. Little wonder that it takes longer to cook. The meager browning you see when frying with fresh oil is a dead giveaway that caramelization and Maillard reactions haven't occurred, so the food is bound to lack flavor, too.

After repeated use, frying oil goes through another set of chemical reactions, called hydrolysis, that split and rearrange some of the fat molecules. Among the new reaction products are **surfactants**—also known as **emulsifiers**—that allow oil and water to mix. (Dishwashing detergent is one familiar example of a surfactant.)

Food cooked in oil that's been "broken in" this way will spend upwards of half of the total frying time in contact with the oil. With heat being delivered more rapidly, the food cooks faster to higher temperatures, an even golden-brown color, and a more robust flavor.

Unfortunately, oil cannot be kept in its peak

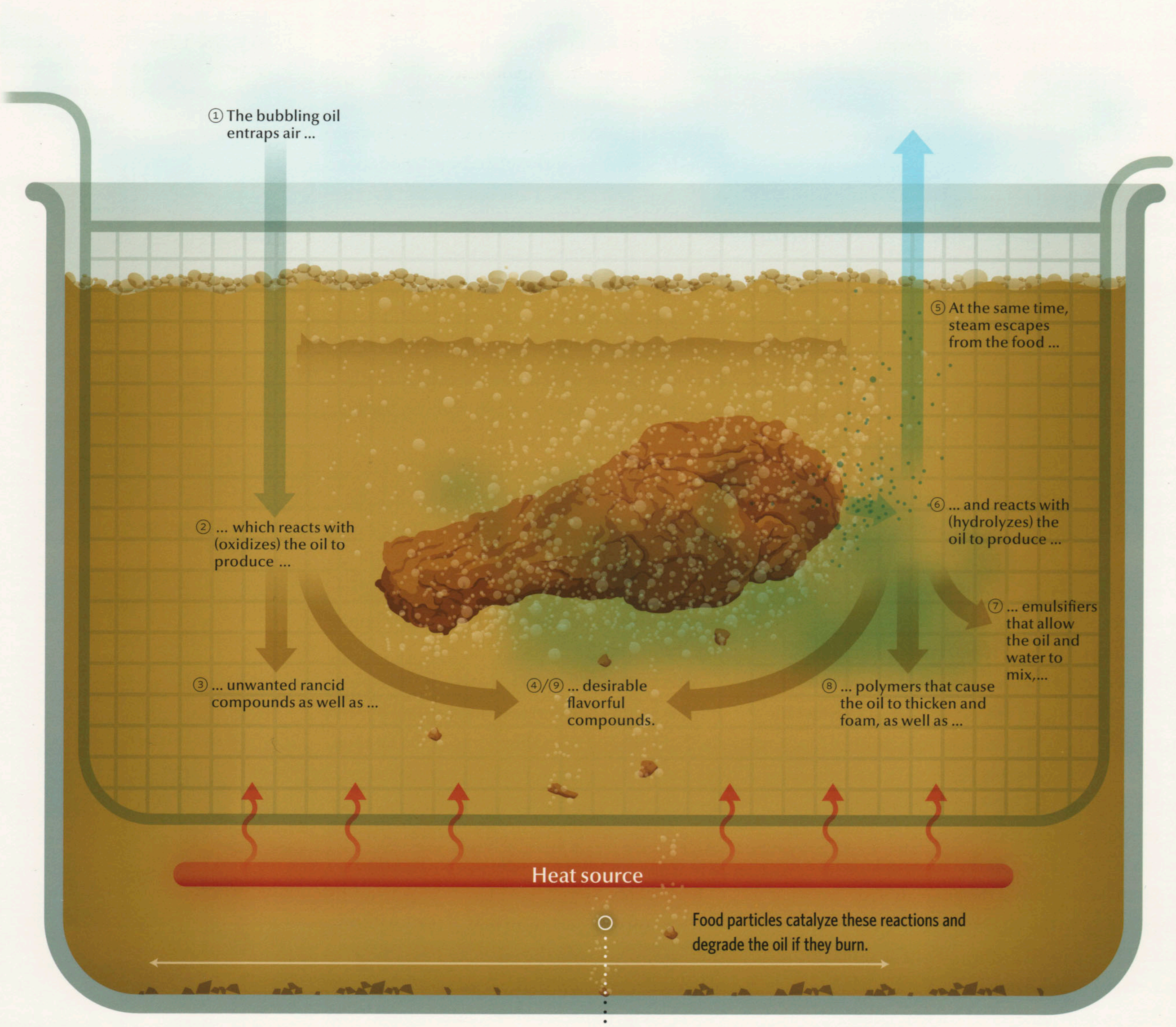
The best way to break in new oil quickly is to add just a few teaspoons of old oil. The old oil contains highly reactive compounds that will promote desirable chemical cascades in the fresh batch. Don't overdo it; a little of these unstable compounds goes a long way.

American food chemist Michael Blumenthal described the role of emulsifiers in deep-frying in the late 1980s. Before then, the chemistry of "breaking in" frying oil was utterly mysterious, even to the most experienced cooks.

The Secret Life of Frying Oil

The intense heat of deep-frying actually cooks oil, causing a series of complex chemical changes that create the characteristic flavors and textures we associate with deep-fried food. At first, these changes improve the quality of the oil, so it cooks and browns food faster and more evenly. But with repeated use the concentrations of certain compounds build to levels that ruin the flavor of the food and can leave the crust scorched and greasy. Some of the chemicals can even endanger your health. So change your frying oil regularly, and, if you're using a pot of oil or a noncirculating heating bath for deep-frying, strain the oil often to remove food particles.

The blue smoke sometimes seen above a deep fryer is a telltale sign of oil that is too hot, too old, or both. Microscopic soot particles and oil droplets create an aerosol that scatters light—the same phenomenon, known as Tyndall scattering, that makes blue eyes blue. Both haze and oil contain acrolein, a toxic by-product (used in tear gas) that appears when oil breaks down from excessive heat or repeated use.



Food particles catalyze these reactions and degrade the oil if they burn.

A cool zone beneath the heating element collects food particles and prevents them from burning.

condition forever. The reactions that improve it ultimately ruin it. Emulsifiers accumulate each time the oil is heated, so eventually the oil and water mix too well, and the oil spends too much time in contact with the food, causing scorching. Fragments of fat molecules also polymerize as the oil is used, creating sticky gums that thicken the oil, so it clings to food as it is pulled from the deep fryer.

You know your frying oil is shot when the oil starts to foam as steam bubbles get stuck in this goo. Another sure sign of old oil is a rancid, fishy aroma—the result of oxidation reactions gone too far.

Old frying oil isn't just sticky and smelly: it's downright dangerous. The chemical degradation of the oil lowers the smoking and flash points, increasing the risk of a dangerous grease fire.

Old oil also accumulates high levels of acrolein, acrylamide, and other toxic compounds, many of which are created in charred bits of food that build up in frying oil over time. Bits of food are precisely why deep fryers are designed to have their heating element raised above the bottom of the fryer: it creates a cool zone underneath that accumulates those stray bits and keeps them from burning—but only for a while. This is why it's a good idea to strain out food particles that break off during deep-frying. If they start to burn, they'll ruin the oil.

Taming Grease

If bubbling steam prevents oil from infusing into deep-frying food while it's cooking, how is it that poorly fried food is so often greasy? The answer lies in what happens to the food after the fry cook removes it from the oil and it begins to cool.

Those same volcano-like fissures and holes in the food through which steam escaped now become caves of condensation (see diagram below). As vapor condenses back to water in the crust, it creates a slight vacuum that sucks in oil from the surface. Capillary action then does most of the work of making food greasy by piping the oil deep into the dried crust.

Simply blotting deep-fried food as soon as it emerges from the fryer will make it a lot less greasy. But take care that you don't remove all of the oily coating. Oil is, after all, the source of much of the flavor, texture, and mouthfeel of deep-fried food.

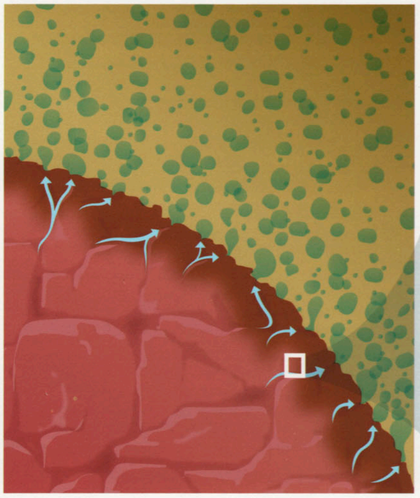
These sensual effects are confined to the food surface, but that's right where they need to be. When we take a bite of fried food, our tongue, cheeks, and palate sense the surface first; subsequent chewing mixes the warm, aromatic oils together with the rest of the food.

Rather than stripping off all of the oil, the goal of deep-frying should be to leave food coated with just the right amount: neither too little to impart the desirable deep-fried characteristics,

Blanch food before deep-frying to form a kind of skin that resists the absorption of oil. To enhance this effect, add salt to the blanching water—0.5% calcium chloride works especially well.

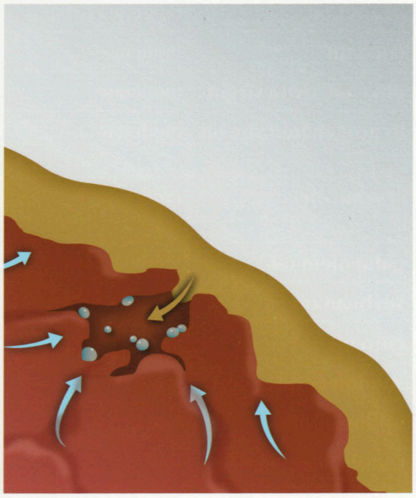
The "water fryer" is a Japanese invention that has the ultimate strategy for dealing with crumbs at the bottom—it has a layer of water several centimeters (a few inches) deep at the bottom of the fryer. Since oil floats on water, it stays at the bottom. The water is far below the heating element, so it doesn't get hot enough to boil. Any crumbs fall into the water and thus do not burn.

Overloading a deep fryer is a sure route to greasy food. Crowding food into the fryer lowers the oil temperature, which in turn yields a crust that is thick, leathery, and a sop for excess oil.



Steam "volcanoes" form when hot oil boils water in the food, which migrates to the surface from the interior.

The steam, erupting through surface pores and fissures, prevents oil from penetrating the food during cooking.



After cooking, condensation creates a vacuum that draws oil in; capillary action then wicks the oil still deeper.

THE CHEMISTRY OF

Choosing an Oil

Cooks increasingly use neutral-flavored, unsaturated oils for deep-frying; many believe that foods fried in such oils are more healthful than those cooked in traditional frying oils. Many other factors are worth taking into account when choosing a deep-frying oil, however. Although "saturated" has become a dirty word in certain circles, the fact remains that saturated oils are often the right choice for deep-frying.

Flavor is an important factor that just about everybody cares about. But some neutral-flavored, unsaturated oils can present problems. When McDonald's traded the beef tallow in its deep fryers for unsaturated oils in 1990, for example, the chain found that it needed to add tallow flavoring to augment the vegetable oils in which it cooks its French fries. Otherwise, the fries just didn't taste right.

Mouthfeel, another crucial component of taste, can come into play as well if the food will be served cold. Potato chips, for example, should be made by using a fat that melts in your mouth, which means the melting point of the oil must be below body temperature. Otherwise, the chip will be unpleasantly tacky and greasy.

Most saturated oils—and even some partially unsaturated oils—melt well above body temperature, so they are not suitable for frying foods served cold. Glazed donuts are a notable exception to this rule. If you don't want the glaze to crack, you'll need an oil that leaves a coating of solid fat at room temperature.

A final important consideration is the stability of the oil. Saturated oils are generally more stable than unsaturated oils, so they stay in peak frying condition longer. The saturated variety are also much less prone to rancidity both in the deep fryer and on stored fried food.

In unsaturated fats, the polyunsaturated molecules cause the fat to degrade much more quickly as rancid aromas and toxic compounds form. The short batch life of unsaturated oils can make them more costly than saturated oils.

The table below lists important characteristics for some of the more common refined frying oils.

Common Frying Oils

Fat	Stability	Melting point (°C)	(°F)	Smoke point (°C)	(°F)	Flash point (°C)	(°F)	Notes
beef tallow	very high	54	129	205	400	260–290	500–554	distinct aroma
duck fat	high	54	129	190	375	varies		
chicken fat (schmaltz)	high	54	129	190	375	varies		
palm oil	high	37	99	215–230	420–445	300	570	minimizes off-flavors very well
pork lard	high	33	91	185–205	365–400	200–280	390–535	
cottonseed oil	moderate to high	-1	30	215	420	230	445	
peanut oil	moderate to high	-2	28	225–230	435–445	280	535	high-quality oil; allergenic
coconut	moderate	25	77	175	345	215	420	can smoke excessively if unrefined
olive oil, extra virgin	moderate	-6	21	210	410	232	445	distinct flavor; can turn acrid
hydrogenated soy oil	moderate	45	113	230	445	325	615	characteristics vary with amount of hydrogenation
sesame oil	moderate	-5	23	210–215	410–420	255	490	high-quality oil; available toasted and untoasted; high in antioxidants
palm olein oil	moderate to low	10	50	215	420	varies		may discolor before oil is degraded
soybean oil	moderate to low	-16	3	230–255	445–490	280	535	prone to off-flavors
corn oil	moderate to low	-11 to -8	12–18	230	445	275	525	drains well
sunflower oil	low	-17	1	225–245	435–475	275	525	poor-quality oil; tends to foam
safflower oil	low	-17	1	230–265	445–510	260	500	
canola (rapeseed) oil	low	10	50	205–240	400–465	250	480	prone to off-flavors without treatment; readily absorbed by food
grapeseed oil	low	10	50	200	390	250	480	rich in fatty acids; oxidizes easily

nor so much that the flavor and texture of the food itself are obscured.

To control the oil coating, you need to know what factors affect it. One is the age of the oil; older frying oil becomes more viscous, so it clings more stubbornly to the food than fresher oil does.

Frying temperature matters, too. Oil thickens as the temperature drops, so less of it will drain from the surface if you cook at lower temperatures. Exacerbating that effect, lower frying temperatures also tend to produce a thick, leathery crust that absorbs more oil after cooking.

Cooking French fries in oil just 10 °C / 18 °F below the recommended temperature of 180–185 °C / 355–365 °F can increase the oil absorption by 40%. To minimize grease and get a thin, delicate crust, it's always best to deep-fry at the highest temperature practical—but not so high that your crust burns or scorches.

A third variable is the thickness of the food. Thin foods have proportionally more crust than interior volume, and the crust is where oil is absorbed. So it stands to reason that, weight for weight, potato chips can absorb two to three times more oil than the same amount of French fries, simply because the chips are all crust.

Then there's surface roughness to consider. Make your chip just a bit thicker and you will dramatically reduce the amount of oil that gets trapped on the surface. That's not just because the proportion of crust to interior is smaller, but also because thick chips crack and blister less when they cook, and oil easily drains off a smoother crust. There's a trade-off in texture, of course; a thin chip will shatter crisply in your mouth, whereas the thicker chip will be hard and crunchy.

Batter-coated foods present the greatest challenge to fending off grease. Coatings become thick, dry, and rough crusts—precisely the kind that absorb the most oil. There are, however, some tricks to making batters that yield a less oily crust. Add egg white and a small amount of calcium chloride to a batter to make it crisper while also forming an invisible, protective film that reduces oil absorption. Most hydrocolloid and starch manufacturers produce specialty blends of gums, gels, and salts for the same purpose; these can give better results, but they are more difficult to procure.

A schnitzel is the canonical example of a shallow-fried food. The breaded cutlet is too broad and flexible to hold a good shape in the deep-fryer, but only a good drenching in very hot oil puffs and crisps its batter properly.

Shallow Frying

Shallow frying takes place in a pan rather than a fryer, but don't be fooled: it's more akin to deep-frying than to panfrying. If you think of the technique as deep-frying in the shallow end, you'll be less likely to skimp on the oil—and a surfeit of oil is the key to a good shallow fry.

Many home cooks wonder why their panfried chicken breasts or fish fillets fail to turn out as well as the ones they enjoy at finer restaurants. The reason is that professional cooks load up their frying pans with oil—far more than they'd use for a textbook panfry and far more than most home cooks use. The pros are actually shallow frying, whether they call it that or not.

Shallow frying is probably a more common technique than deep-frying because it requires no special equipment. The cooking process can be uneven; any hot or cold spots on the bottom of the pan will create hot and cold spots in the oil. The deeper the oil in the pan, the more time heat has to spread sideways—parallel to the pan surface—before it comes into contact with the food.

A generous amount of oil avoids unevenness in still another way. Jets of steam issue from the bottom of the cooking food. If there's too little oil in the pan, those eruptions can actually push the food off the pan and out of the oil. If some parts of your food are scorched, while others are undercooked,

soggy, or greasy, this is probably the cause. Add a deeper layer of oil, and the steam jets will then mix the hot and cold layers rather than segregate them. The food will heat faster and more evenly.

So be generous with oil, and don't worry that you'll get a greasier result. In shallow frying, counterintuitively, more oil yields *less* grease. A too-thin layer of oil causes the cooking temperature to plummet, leading to a thick, chewy sop of a crust. Deep oil will keep the temperature high and the crust thin and less absorbent.

Confit the Easy Way

Among the many techniques of traditional cooking, confit is steeped in perhaps the most mystique. Cooks speak with awed reverence about the process of slow-cooking meat in smothering volumes of rendered fat. The sublime richness of a confit can be terrific, but don't confuse the results with the mode of preparation.

Confit originated as a means of preserving meat for unrefrigerated storage. Now that that purpose is outdated, it's possible (and far more convenient) to achieve the same rich product by cooking it some other way—including a low-fat technique such as sous vide (see chapter 9). If you want the mouthfeel of the fat, simply anoint the surface with fat after cooking.

When making confit, cooks traditionally cure the meat or seafood partially with salt and saltpeter (nitrates and nitrites), then simmer it in oil. In ages long past, the curing step served a critical function: it destroyed the lethal anaerobic bacteria that would otherwise flourish once the meat was sealed, unrefrigerated, inside its protective barrier of solidified fat. Likewise, during the simmering step, the partly cured meat had to be completely enveloped in oil to prevent contamination. Thus cured, cooked, and sealed, the food was botulism-free, impervious to spoilage by oxidation or bacteria, and safe to keep for months.

Now that the modern convenience of refrigeration has eliminated the requirement for preservation, taste is the new imperative in confit. A traditional confit is so salty that you have to dilute the salty taste before serving, either by soaking the food in fresh water or by shredding it and mixing it with other ingredients. Contemporary recipes use much less salt in the curing step for a milder result; some cooks have abandoned curing their confits altogether.

Cooking in fat is irrelevant to the final product, which depends on the time and temperature. All that's needed to transform a simple cooked piece of meat into a sumptuous confit is an oily coating with the fat of your choice. Add the fat while the food is still hot, and let the food cool slowly enough to absorb as much of the oil as possible—although the amount absorbed will be tiny.

Most modern preparations of confit do not preserve the meat, a fact that is sometimes dangerously overlooked. Without salt curing, the cooking process pasteurizes but does not sterilize the meat. Uncured confit meat is thus no different than meat cooked sous vide and stored in its airtight packaging. It's essential to refrigerate modern confit, and the same safety considerations that apply to sous vide with regard to toxic anaerobic bacteria also apply to an uncured, traditional confit (see chapter 3 on Food Safety, page 1·162).

THE TECHNOLOGY OF
Vacuum Frying

Vacuum fryers avoid the problem of browning or burning sweet foods by cooking at lower pressures and temperatures than ordinary deep fryers do. Because the vacuum lowers the boiling point of water, a vacuum fryer dries and fries quickly, despite the lower temperature.

These attributes make vacuum fryers popular for preparing the fried fruit chips that are common in Southeast Asia. But these fryers have some limitations: you can't see inside to check for doneness, for example. And because oil is more viscous at low temperatures, vacuum-fried food tends to be greasy.

CONTROVERSIES

Must Good Confit Be Cooked in Fat?

Based on extensive experimentation, we can assert with confidence that confit can capture just as much sumptuous decadence when cooked sous vide with just a coating of delicious oil as it does when cooked traditional-style, in a vat of rendered fat.

We know many will find this recommendation improbable. Indeed, when we tell cooks about the results of our confit experiments, most simply don't believe us. But this isn't a question of belief: this is something you need to try for yourself. Make it both ways. Then decide whether there is or isn't a difference.

Before you start, keep in mind that a simple side-by-side tasting is the wrong way to judge differences between foods. The right approach is a triangle test (see page 4·336) or a square test (see page 299) in which testers compare multiple samples.

We performed this experiment with duck confit and pork carnitas. In each case, we prepared one batch traditionally and made a second batch by cooking the meat sous vide or steaming it. We then anointed it with oil (duck fat for duck, pork fat for pork). We could easily distinguish among pork or duck samples cooked for different times or at different temperatures. Confit cooked at 60 °C / 140 °F for 24 hours is quite distinct from that cooked at 80 °C / 176 °F for eight hours.

When we compared samples cooked at the same time and temperature, we were unable to tell those cooked in traditional confit style apart from those cooked sous vide or steamed in a combi oven. Note that all of the samples were dressed with a bit of oil before tasting.

If this approach strikes you as superficial, remember that even in a traditional confit, as in deep-frying, oil doesn't diffuse through the surface of the meat while it is cooking. Only as the meat cools does the surrounding oil seep in—and in confit, not very much of it.

Even then, the wetness of the food just beneath the surface stops diffusing fat molecules in their tracks. Ultimately, oil travels no more than a millimeter or so into the meat's interior. But that's far enough because it's the fat at the surface that counts when we taste and chew.

If you're willing to try confit without oil, by far the easiest way to prepare a modern confit is sous vide. It provides a clean, reliable way to cook the meat, and the snug-fitting bag keeps the fat close to the surface of the meat as it cools after cooking.

Some cooks have complained that sous vide confit lacks a certain soulfulness. They may be referring to the missing flavor of oxidation: not oxidation of the food, but oxidation of the fatty coating, which causes the nutty aromas of a traditionally aged confit. The vacuum inside the sous vide bag does prevent this slow oxidation. You can restore it, however, by aging the rendered fat before applying it or by opening the sous vide bag once the food has cooled, thus exposing the fat to air.

THE FUTILITY OF FAT-IMMERSION CONFIT

Duck confit is one of the great traditional dishes of France. Tough duck legs, which are otherwise problematic to prepare, are cured with a salt-and-spice rub and then slowly poached in fat for eight hours or more. Once cooked, they are enrobed in a thick layer of solidified fat, which is removed just before service. The unctuous texture of duck leg confit inspired chefs to start cooking other foods in oil at low temperatures. The oil, it turns out, is irrelevant to the taste and texture of the dish, which actually comes from cooking the duck slowly at low temperature. These days, confit is better made sous vide or by other means—for a recipe, see page 5·82.

Absence of bubbles is a sure sign that the oil is not displacing water from the food. That means there is no place for oil to go in the food; it cannot penetrate the interior. The few small bubbles that can be seen are filled with air emerging from tiny fissures in the food.

Caramelizing and browning do not occur on food cooked confit because the surface never gets hot enough for these chemical changes to occur.

No steam emerges from the surface of the food, so a boundary layer of cool oil surrounds the food and insulates it from the hot oil.

The surface doesn't dry, so it remains at the wet-bulb temperature, which cannot go above the boiling point of water. Most confit is cooked at far lower temperatures, typically 80 °C / 176 °F for traditional confits.

Heat conducts slowly to the interior of the food, despite the high temperature at the surface.

SMOKING

How does wood burn? Few of us pause to wonder. Yet the incandescent warmth of fire, the sight of the dancing flames, and the unmistakable smell of smoke evoke feelings that go to the very core of our humanity. Our earliest ancestors undoubtedly felt the same sense of comfort that we do when gathered around a wood fire, as well as the same fear of an uncontrolled blaze.

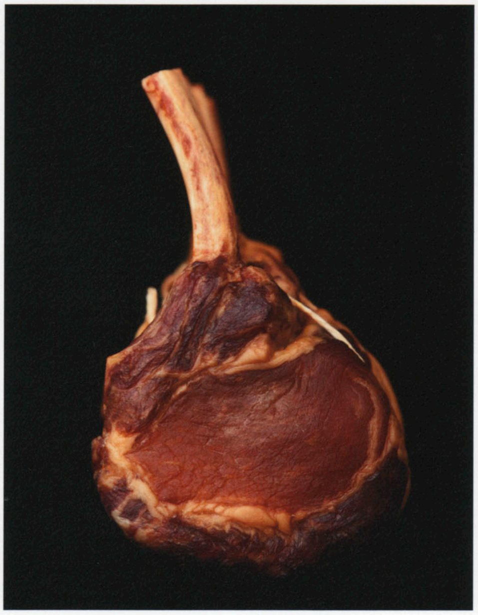
Prehistoric humans, however, developed a mastery of fire that few of us possess today. Lacking matches or accelerants, they learned to start a fire by rubbing the tip of a stick vigorously against a dry log. The friction charred a small spot on the log that would smoke and then ignite with continued rubbing. Our ancestors had no understanding of the nature of combustion, but they could see for themselves that wood becomes smoking hot *before* it burns. Today we say, "Where there's smoke, there's fire." But our ancestors knew that smoke can pour indefinitely from hot, smoldering wood that never bursts into flames.

That, indeed, is usually the ideal arrangement for smoking food. The vapors released from wood on the brink of burning contain a smorgasbord of aromatic compounds that impart smoking's most distinctive flavors. Lower the temperature of the smoldering wood, and you lose some of those flavors while releasing less desirable ones. Burn the wood outright, and it lofts vapors with flavors that, while worthy, are more delicate and fleeting.

The temperature and humidity of the smoke itself are just as important. Hot-smoking perfuses food with flavorful compounds in different proportions than cold-smoking does, so the same food tastes different when smoked hot and cold.

Contrary to popular kitchen wisdom, smoking's various grails—the deep, vivid smoke ring; the dry, tacky pellicle; the pellucid surface sheen—do not themselves affect the aroma or taste of smoked food. These are symptoms—not causes—of the changes we expect from smoking.

Creating and controlling smoke may be a lost art these days, when many of us struggle to build a fire even with the aid of matches, fake logs, and petroleum starters. A return to first principles can help recover that primeval understanding of why and when wood smolders and burns. You need that knowledge to create quality smoke. And if you also understand some of the basic chemistry of smoke, you gain control over its effect on flavor and appearance.



Smoked chickens and pork chops develop very similar colors despite being quite different meats. The color as well as the flavor of smoked food comes from the invisible vapors transported in smoke reacting with proteins common to all meats and seafood.

Making Smoke

For more on the structure of plant tissue, see Plants as Food, page 3·262.

When making charcoal, you want to starve the smoldering wood of oxygen while holding the temperature well above 450 °C / 840 °F. Almost everything in the wood then either vaporizes or **pyrolyzes**, leaving just a shell of carbon and ash.

Smoke originates from wood, a plant tissue that shares some structural similarities with other plants but differs in a few crucial details. Like plants that we eat, wood comprises cells encased in rigid cell walls. Each cell wall is made of cellulose fibers stitched together by pectin and hemicellulose molecules. When you steam broccoli or bake rhubarb, the heat softens the rigid cellulose and dissolves pectin and hemicellulose polymers, thus tenderizing the food and making it easier to digest. Even raw, however, edible plants are weak compared with wood. You wouldn't want to build a house with rhubarb.

Wood, on the other hand, is strong enough to use in construction because its cell walls are impregnated with high amounts of **lignin**, a tough, inflexible compound renowned for its resilience. Lignin accounts for one-fifth to one-third of the weight of most woods.

Lignin is hopelessly indigestible to all but specialized microbes: no amount of cooking will ever make it edible by humans or any other animal. That's why people can starve in the middle of a forest. And it's why we cook with wood, rather than eat it.

Lignin is also what makes smoked food delicious. Most of the aromatic compounds that impart the characteristic smoked flavor originate with this complex chemical. At temperatures higher than about 300 °C / 570 °F, lignin molecules break down into a wide range of volatile chemicals called **phenols** that yield earthy, warm notes such as peat, clove, and vanilla. Mesquite is aromatic because it has more lignin than most woods. Wood from pine trees produce a harsh, acrid smoke, in large part because their lignins produce different phenols than those of hardwoods. In addition to imparting flavor, many phenols are potent antioxidants that prevent rancidity—one reason smoking helps to preserve food.

Food scientists have found that the smoke produced by hardwoods smoldering at tempera-

Smoldering wood releases chemicals called phenols, carbonyls, and other aromatic compounds that impart the rich, complex flavors of smoked food.

THE CHEMISTRY OF

The Perfect Temperature for Smoking

Heating wood cooks it, and just like food, you can overcook or undercook it when you make smoke. As soon as the temperature exceeds about 65 °C / 150 °F, cellulose and hemicellulose molecules begin to slowly degrade, just as they do in edible plants. At the boiling point of water, vaporizing steam allows carbon dioxide trapped in the wood to start to escape. Some of that carbon dioxide reacts with the charred wood to make carbon monoxide and nitrogen dioxide, crucial ingredients that form the smoke ring that appears in some smoked foods.

Wood (especially wet, green wood) may appear to smoke around 100 °C / 212 °F, but what you're actually seeing is fog condensing from the steam released as the wood dries out. That fog contains none of the coloring compounds or flavorful aromatics produced at higher temperatures, so it is usually better to begin with dry, seasoned wood.

Once the wood has dried out, it can get hotter. At 170 °C / 340 °F, the wood starts to char, and the first wisps of true smoke rise into the air, visible signs of a chemical process called **pyrolysis.**

More violent than the molecular unraveling that occurs when edible plants are cooked, pyrolysis actually breaks molecules apart into simpler compounds. Low-temperature pyrolysis dismembers cellulose and hemicellulose, for example, yielding acetic acid (vinegar), formic acid (which puts the sting in ant bites), and other tart acids. Little surprise, then, that smoke from low-temperature smoldering smells acrid and can taste awful. The acids play an important role in smoking nonetheless because they are largely responsible for its preservative effect and essential for proper color development on the surface of meats and seafood.

The smoke begins to mellow when the wood reaches 200 °C / 390 °F or so, at which point the production of volatile acids diminishes and pyrolysis starts to produce aromatic molecules called **carbonyls.**

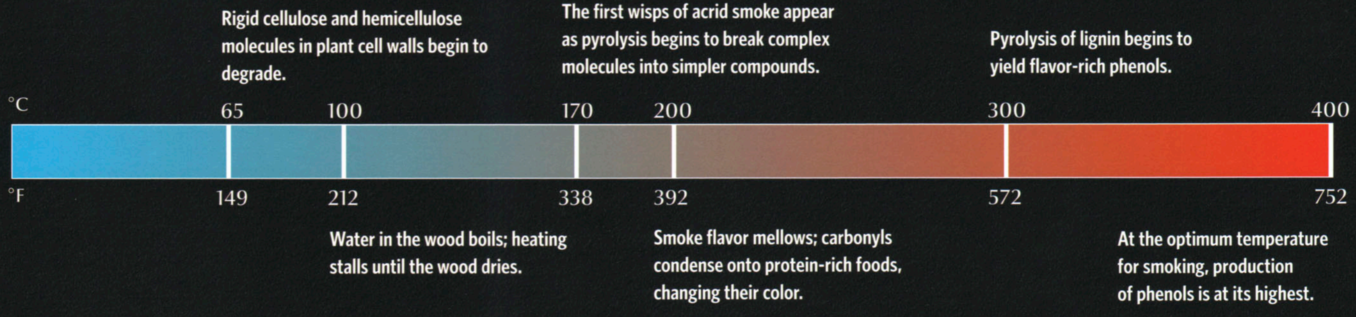
When the carbonyls condense onto the surface of drying meats, seafood, cheese, or other protein-rich foods, some of them react with amino acids and sugars in the food in a Maillard-like reaction that generates both new aromas and the dark red, brown, and yellow colors so characteristic of smoked food. Other kinds of carbonyl molecules, such as formaldehyde, join with the volatile acids to enhance their antimicrobial, preservative action.

In smoking, as in steeping tea, color can develop before flavor does. Not until temperatures reach 300 °C / 570 °F or higher do the **phenols,** with their distinctive aromas, pour into the smoke as the heat pyrolyzes lignin. Isoeugenol contributes notes of clove, creosols evoke peat, vanillin tastes just like it sounds, and guaiacols and syringols provide some spice. Pyrolysis of cellulose and hemicellulose also accelerates and supplies sweet maltitols, furans with toasty caramel overtones, nutty lactones, and the fresh green-apple–like aroma of acetaldehydes.

All of these processes peak near 400 °C / 750 °F, the perfect temperature for smoking. When the wood is charred black and issuing plumes replete with the myriad vapors and liquid droplets that make up a thick, dark, quality smoke, that peak is at hand.

But the wood is not yet actually burning—although by all rights it should be. One of the conundrums of smoking is that the temperatures that produce especially rich, fragrant smoke are higher than the temperatures at which smoldering wood can burst into flame if ignited by a pilot flame (see Playing with Fire, page 137).

Ignition of wood wreaks havoc with smoke. As wood burns, the temperature of the fire climbs rapidly toward 1,000 °C / 1,800 °F. At such high temperatures, pyrolysis emits only the lightest, most volatile molecules in the smoke and incinerates the rest. You can actually utilize this phenomenon when hot-smoking—but you'll want to keep it under tight control.



THE CULTURAL IMPORTANCE OF

Choosing Your Wood

For American barbecue, hickory is the granddaddy of smoking woods, revered for its bold, sweet flavor and the golden brown hue it imparts to the smoking meat.

People in other parts of the world see other woods in much the same way, as an ingredient no less important to the authenticity of the dish than the food being smoked. Cooks in the Pacific Northwest, for example, traditionally smoke their salmon with alder wood, whereas Tex-Mex *barbacoa* is defined by the intense pungency of mesquite.

In the Baltic States, linden is a popular choice for smoked meats and seafood; grapevine trimmings are preferred in Spain, Italy, and France (and everywhere else that produces wine); and the mighty oak tree is a favorite in England. Cooks in China often smoke their meats using tea leaves and wood from the camphor laurel.

Clearly, there is no one best species of wood for smoking, but hardwoods generally work better, producing richer color and bolder aromas than firs and pines.

Good Woods for Smoking Food

Species	Intensity of flavor	Color imparted	Note
grapevine	light	golden brown	among the lightest of smoke types
straw	light	yellow to golden brown	excellent for giving seafood a quick, light smoking
ash, elm, hornbeam, chestnut	light	yellow	typically blended with other hardwoods
tea leaves	light to medium	yellow to light brown	often used for light smoking in parts of Asia
alder	medium	golden yellow to brown	excellent with seafood; sometimes blended with beech
apple	medium	yellow	best of common fruit woods
cherry, peach	medium	yellow	typically blended with other hardwoods
corncob	medium	weakly yellow	pronounced, earthy aroma
heather, dried	medium	yellow to golden brown	unusual aroma and very floral flavor; traditionally used with seafood in Scandinavia and parts of Scotland
mahogany	medium	golden brown	typically blended with other hardwoods
thyme, marjoram, or sage, dried	medium	weak	recommended for light smoking only
walnut	medium	deep yellow to brown	produces rapid color development in meats and seafood
linden	medium	yellow	popular in smoked foods of Eastern Europe
birch, poplar, willow	variable	variable	often blended with beech
hickory	bold	deep yellow to brown	pleasantly sweet aroma
pecan	bold	deep yellow to brown	pleasantly sweet aroma
laurel	bold	weak	distinctive flavor; recommended for light smoking only
rosemary, dried	bold	weak	slightly resinous flavor; recommended for light smoking only
beech	bold	bright yellow	traditionally used with fish; often blended with oak or alder
juniper	bold	dull brown	interesting but intense flavor; suitable only for very light smoking
camphor laurel	very bold	dark yellow to light brown	exotic and intense aroma; camphor is a popular choice for smoked duck in China
oak	very bold	deep yellow to brown	produces very dense, high-quality smoke; flavor overpowering for some foods
mesquite	very bold and pungent	yellow	smolders very hot with an intense aroma and pungent flavor

In Iceland, smoked lamb is a traditional delicacy. But with trees and shrubs in short supply, Icelandic cooks commonly smoke food by burning dried sheep manure instead of wood. Try explaining that on a trendy menu!

tures around 400 °C / 750 °F yields the most flavorful foods. That temperature seems ideal not only because of what then goes into the smoke—the phenols and other aromatic compounds—but also because of what doesn't: namely, excessive amounts of vaporizing acids that taste terrible. For a more detailed explanation of how the smoldering temperature affects smoke quality, see The Perfect Temperature for Smoking, page 135.

Playing with Fire

The title of Ray Bradbury's acclaimed novel *Fahrenheit 451* refers to the temperature at which paper—and the wood it's made from—ignites. (The metric equivalent would be *Celsius 233*.) Yet the ideal smoldering temperature for smoking wood is hundreds of degrees higher than that. How can that be?

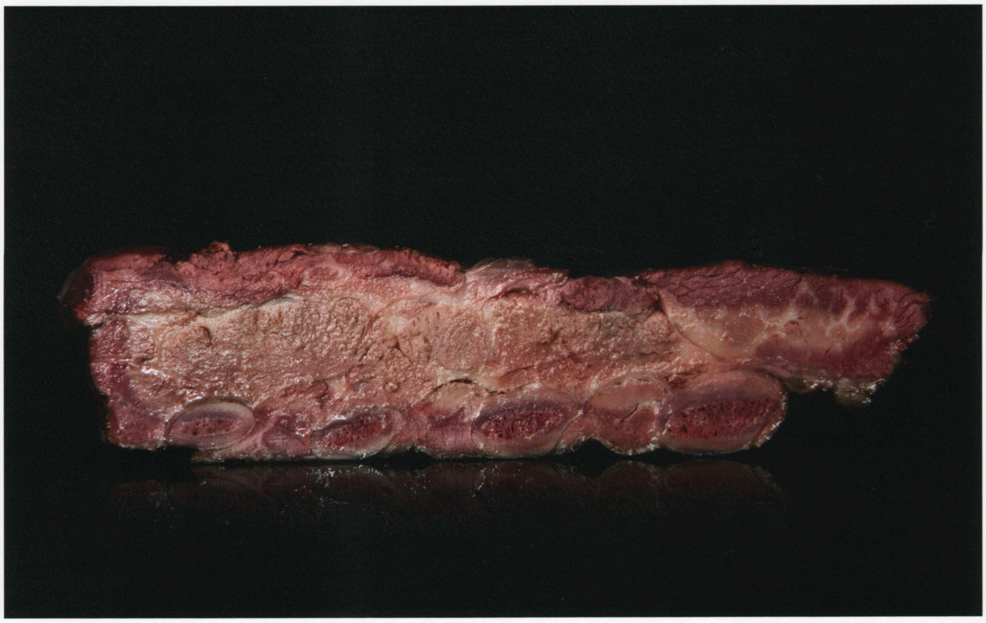
The answer is that at 233 °C / 451 °F, the pyrolysis of wood generates flammable vapors, which will sustain a flame if one is applied (by a match, for example). But absent a spark to get the fire going, smoldering can continue without flames up to about 500 °C / 930 °F. At temperatures higher than that, the vapors **combust** spontaneously, combining with oxygen to make fire, smoke, and ash.

With the right conditions, though, combustion can happen on its own even at 400 °C / 750 °F. When you're smoking at prime temperatures, then, you are literally playing with fire. How can you control whether or not your wood bursts into flames? The trick is to regulate the airflow through the smoker. The more you restrict the oxygen supply to the smoldering wood, the less likely the vapors are to combust, though they may be poised on the brink of deflagration.

Don't be too stingy with the airflow, however. Choke the smoldering wood too much, and its smoke will become deficient in desirable aromatics, such as vanillin, and enriched in carcinogens, such as polycyclic aromatic hydrocarbons. On the other hand, an overabundance of oxygen will stop the formation of sweet maltitols and toasty furans while inviting unwanted flames. Just as there is an art to controlling the heat of a grill, it takes special skill to manage a smoldering fire so that it produces the most fragrant and healthful smoke.

Halibut smoked for several hours shows the bright coloring produced by Maillard-like reactions between carbonyls in the smoke and amino acids and sugars on the drying surface. The interior of the fish remains uncolored because it is too moist to support the reactions.

The bright red smoke ring in this rib is like a watermark that indicates how far adsorbed compounds have diffused into the food. The volatile substances in smoke rarely penetrate more than 1 cm / $^3/_8$ in.



Capturing the Flavor of Smoke

Smoke is much more than a simple gas. In fact, smoke is a mixture of all three states of matter, a blend of solid particles of soot and tiny droplets of liquid suspended in air and vaporized chemicals. Two of these three phases are visible: high concentrations of soot turn smoke thick and black, whereas the translucent droplets of tars, oils, condensing volatiles, and water show up as a wispy blue.

We have seen elsewhere in this chapter that oil and oil-like molecules cannot diffuse through wet food—and this is just as true for smoke. But diffusion is a **bulk phenomenon**, which is to say that it only applies to large collections of molecules, such as droplets. Individual molecules of oil-like smoke compounds do travel slowly through water in the food.

The components of smoke that are in the vapor state, on the other hand, cannot be seen at all—yet it's the vapor that does all the heavy lifting of smoking. Contrary to what you might have heard, the invisible gases in smoke contain nearly all of the compounds that color, preserve, and flavor smoked food. Although they're typically just 10% of the volume of smoke, these gases do more than 90% of the work.

The reason that gases are so important is that most flavor compounds are organic chemicals that, like oil, don't dissolve in water. Food contains lots of water, so liquid droplets from the smoke just bead up on the surface. The flavors they convey thus don't penetrate the food, although they do contribute somewhat to the texture and flavor of the pellicle.

Vaporized organic chemicals, in contrast, float around as solo molecules. When they land on the food, they can **adsorb**, meaning they adhere directly to the food or any thin layer of water or oils that coats it. Once stuck to the food, the flavor molecules react with compounds on the food surface. And, unlike the droplets, they then move inward toward the center of the food—as long as it is neither too dry nor too wet. Just as a thin oil slick can spread through an ocean, the adsorbed organic chemicals can form a sheen on the tacky surface of the food that slowly inches its way through tiny, moist channels in the tissue, ferrying flavors to the interior.

If the outside of the food becomes too dry in the smoker, the smoky flavors can't get very far inside because there is no medium through which they can travel. On the other hand, if the food is too wet, the compounds that come out of the smoke in liquid and gaseous forms tend to drip off the food or to evaporate away. If the food feels warm and slightly tacky to the touch, the exterior moisture is just about right.

Capturing the flavor of smoke thus involves two challenges. The first is making sure the flavor compounds you want are gases, not liquid droplets, when they reach the food. That requires keeping tight control of the temperature of the smoke in the chamber. The second challenge is keeping the food just wet enough to allow the volatile organics in those vapors to stick to the food, form a film on the surface, and then diffuse deep inside. To do that, you must control the humidity in the smoker.

A raw brisket has a dull surface (above left), but as it smokes the meat takes on a glossy sheen (right) that indicates perfect pellicle formation for a red meat partway through the smoking process. The sheen comes from phenols and carbonyls in smoke that react with proteins, sugars, and starches on the food surface.

The Chemicals at Work in Smoking

Smoke is a gaseous marinade of hundreds of chemicals that together contribute the characteristic flavors, textures, colors, and curing we associated with smoked food. Some of the names given below represent whole classes of compounds, such as phenols and carbonyls; others, such as nitrogen dioxide and formaldehyde, refer to specific chemicals.

Effect	Compounds	Actions	Note
color	carbonyls	adhere to the food surface and engage in low-temperature, Maillard-like reactions with high-protein foods	critical reactions don't occur if the food surface is too wet or too dry; reactions don't occur on plant foods, which lack necessary proteins
	nitrogen dioxide, carbon monoxide	adhere to the food surface, then diffuse into food and react with myoglobin in the muscle of meat and fish to produce a smoke ring	wet wood and low smoldering temperatures produce too little of these to create a visible ring; the ring appears only in muscle tissue
flavor	phenols, carbonyls	adhere to the food surface and diffuse into food	not produced by wet wood or low smoldering temperatures; don't penetrate food if the surface is too dry; adsorbed unevenly on surfaces that are too wet or fatty
preservation	antioxidants	inhibit rancidity in preserved foods, especially seafood	not produced by wet wood or low smoldering temperatures
	formaldehyde	coats the food surface, slowing bacterial growth and spoilage	wet wood and low smoldering temperatures produce too much formaldehyde, ruining flavor and posing a health risk
	acids	lower the pH of the food surface, which improves pellicle formation and slows bacterial growth	wet wood and low smoldering temperatures produce too much acid, leaving an acrid flavor
surface finish	phenols, carbonyls	adhere to the food surface and polymerize into glossy resins	not produced by wet wood or low smoldering temperatures; critical reactions don't occur if the food surface is too wet or too dry; reactions happen too slowly for short smoking sessions
surface texture	formaldehyde, creosote	react with proteins to toughen the food surface in a process similar to tanning leather	can make the surface of food, especially skin, too tough during long smoking sessions

Hot Smoke, Cold Smoke

The temperature of the smoldering wood sets the starting blend of volatile compounds you have to work with. But smoke cools on its journey from fire to food, and the temperature of the smoke in the food chamber is what ultimately determines which flavor compounds will reach the food in the vapor form that is most useful.

Temperature matters because the volatiles have a wide range of boiling points. In general, molecules that are big and heavy—like hefty isoeugenols and vanillin, which contribute clove and vanilla accents—start condensing into droplets at pretty hot temperatures. So, whereas vanillin can permeate deeply into a hot-smoked food, cold-smoking diminishes vanillin's contribution to the flavor. When the smoke is colder, most (but not all) of the vanillin and other very heavy compounds reach the food in the ineffective form, as liquid droplets.

You're thus not likely to find strong tastes of vanilla and cloves in cold-smoked foods. Instead, their flavors are dominated by lighter compounds that remain vaporized in the cooler smoke. Some of the crucial chemical players are carbonyls, which contribute color, and a subset of flavorful aromatics: phenols; sweet-smelling maltitols; furans that add toasty notes; earthy- and spicy-smelling syringols and guaiacols; and the very smoky-smelling creosols.

The lightest volatiles, which include carbon monoxide and nitrogen oxide, have boiling points so low that they remain gaseous even at refrigerator temperatures. Because of this fact and their small size, these compounds go deepest into the food. In meats and seafood, you can often tell exactly how far they traveled into the interior by looking at the smoke ring, a kind of watermark that the two compounds leave behind when they react with the myoglobin in muscle tissue. The smoke ring doesn't contribute any flavor itself, but you can be sure that no flavorful vapors have gone beyond that line.

The smoke ring is often considered a proxy for good technique because it's a sure sign that flavorful vapors have diffused into the food interior. The

truth is a bit more complicated. Some smokers and some styles of smoking do not produce enough carbon monoxide and nitrous oxide to make a visible ring, yet they can still produce very good smoked flavor. Also, smoke rings won't form in foods that don't contain myoglobin—that is, in any foods that aren't muscle tissue.

Thus, the smoke ring is a sufficient indicator of technique, but not a necessary one. Let taste, rather than the presence of a flavorless smoke ring, be your guide to the quality of smoked food.

Wet Food, Dry Food

Meeting the second challenge of smoking—ensuring your food stays moist enough to capture flavorful vapors but is not so wet that it drips—usually means, in practice, adding humidity to the air in the smoker. Smoldering wood produces a dense smoke that is far drier than the relative humidity of 70%–80% that is usually ideal. Advanced smoking equipment controls humidity directly by adding the right amount of water vapor to maintain a desired relative humidity. In more traditional equipment, you can counter the parching effect of smoke by placing broad, shallow trays of water in the bottom of the smoker or by frequently misting warm water into the chamber.

Complicating matters is the fact that the humidity in smokers varies constantly and evades direct measurement. Relative-humidity meters are of limited use in smoking chambers because they quickly become coated with particles of soot and droplets of tar that compromise their accuracy. Sophisticated smokers use wet- and dry-bulb thermometers to calculate relative humidity instead.

Ultimately, of course, your main concern is not the humidity per se but how fast and far the smoked food has dried. The best gauge of that is the **pellicle,** the coating that forms from vapors, oils, and tars in smoke as they react with proteins, sugars, and starches on the food surface. Phenols and carbonyls that adhere to the surface react to become glossy resins that impart a shiny finish. In high-protein foods, formaldehyde and creosote also firm the surface in a process similar to tanning.

A skilled craftsman can watch the development of the pellicle and know whether or not the drying is going right or horribly wrong. A dry, tacky pellicle with uniform coloration is a sure sign of quality smoking. Such a pellicle contributes directly to the flavor and texture; it also confirms that conditions were optimal for the adsorption and diffusion of flavorful compounds.

A hardened pellicle, on the other hand, signals overdrying, and a pale, wet, or streaky one means that the food was too wet. If too much water accumulates on the surface, Maillard-like reactions between carbonyls and the food can't happen, and proper color and flavor won't develop. Texture can suffer as well. Hot-smoking fish at a relative humidity above 60% at 50 °C / 122 °F (or lower humidities at higher temperatures) quickly gelatinizes collagen fibers. The weakened flesh tears under its own weight, often right off the hook.

Cold-Smoking

Traditionally, smoking was a way to preserve food in the absence of refrigeration. The volatile acids in smoke kill bacteria on the surface of food, and

Although it's common practice, we don't recommend wetting wood chips to increase humidity. Wetting chips lowers the temperature of the smoldering wood so much that the smoke can turn acrid.

The tanning properties of smoke can be problematic for poultry, making the skin too tough and leathery.

Wood pellets (left) and chips (right) are both perfectly acceptable fuels for smoking. Pellets work best in smokers that have a hopper or an augur system; chips are fine for hand feeding.

Cold-smoked salmon belongs to a long tradition of cold-smoking seafood that includes preparations as diverse as Scottish finnan haddie and Japanese katsuobushi. Fish is more commonly cold-smoked than hot-smoked because its delicate flesh can tear if the smoke gets too hot or the humidity climbs too high.

thorough drying discourages microbial activity throughout the food interior.

But cold-smoking, as the name suggests, typically takes place at 20–30 °C / 68–85 °F or lower, temperatures that are too cool to pasteurize food. Moreover, the drying stage often involved in cold-smoking can take days or even weeks to complete—days and weeks in which the smoking food is vulnerable to the growth of microbial contaminants. As a result, many traditional cold-smoked foods are first treated with curing salts, particularly nitrate and nitrite salts. The cures prevent the growth of anaerobic bacteria and, in combination with smoke, inhibit the production of the spores that cause botulism.

These days, cold-smoked food is preserved mostly in refrigerators, and we prize it less for its shelf life than for its unique flavors—in particular, the warm and peaty notes of creosols and maltitols, which stay in the gaseous phase even at relatively cool temperatures. Contemporary practitioners don't use nearly as much salt as was the historical norm, and some no longer cure the food at all. Thanks to refrigeration, the long drying stage isn't strictly necessary, either.

If you abandon the curing and drying steps, however, be aware that you do invite some hazards. The cold-smoking chamber can be a breeding ground for anaerobic bacteria, so it's unwise to cold-smoke at room temperature for more than four hours. Consider decontaminating the food surface by either blanching or parcooking before smoking. And if you're cold-smoking sausages or other forcemeats, you must add curing salts (in many places, this is more than just sound advice; it's also a legal requirement). You can safely cold-smoke for longer times without taking these precautions only if your smoker operates at refrigeration temperatures (10 °C / 50 °F).

Even if you don't have to add curing salts for safety, you may want to do so for practical reasons. In cold-smoked meats and seafoods, the salts accelerate the formation of a pellicle, which otherwise appears only slowly as drying limps along. Curing salts draw proteins, sugars, and other small molecules to the food surface, where they concentrate. The effect, which occurs with even a very brief salt packing, creates a good base for faster reactions with the vapors in the smoke.

But if you want to re-create the traditional dry texture of food cold-smoked over days and weeks, there are no shortcuts. The extended drying cannot be fully replicated in any other way.

The challenge, then, is to keep the temperature and humidity of the smoke just right for such long periods. If the smoke is too warm, too dry, or both, then evaporation at the surface of the food outpaces the migration of water from the interior, and a crust forms that seals moisture in the food. This unfortunate condition is known as case hardening, and it tastes as bad as it sounds.

Many cooks try to meet the challenge simply by wetting their smoldering wood, hoping that this will raise the humidity and lower the temperature of the smoke. It will—but it will also make the food acrid because the wood will smolder at a much lower temperature than is ideal. A better strategy is simply to move the fire box further away so that the smoke cools more before reaching the smoking chamber, where you raise the humidity with trays of warm water.

Some high-tech smokers have refrigeration coils in the chamber that make it easy to control the smoke temperature accurately. These devices usually also offer a way to inject low-temperature steam into the chamber to control the humidity directly. This sophisticated smoking equipment comes at a cost, but if smoking is a centerpiece of your cooking, the extra control and flexibility are probably worth the investment.

Hot Barbecue

At the high temperatures at which you hot-smoke food—at least 52 °C / 125 °F, but more often 70–80 °C / 160–175 °F—the potent clove and vanilla flavors of the heavier volatile compounds dominate. Smoking times tend to be much shorter than those for cold-smoking because in contemporary hot-smoking the goal is to cook the food and pasteurize it rather than to dry it out to preserve it. The higher heat hastens the formation of a colorful, glossy pellicle, and the shorter cooking time means that humidity control is less of a problem, too.

One notable exception to this generalization is American-style barbecue. In barbecue, smoking times commonly reach eight hours and beyond. The slow, humid cooking tenderizes the meat as it smokes by dissolving collagen.

In one style of American barbecue, whole hogs

Cold-smoked food is low in polycyclic aromatic hydrocarbons, carcinogenic compounds that condense out of smoke vapor at low temperatures. Early evidence for the presence of these toxins in wood smoke came from the high rate of cancer in chimney sweeps.

The epitome of traditional cold-smoking for preservation is *katsuobushi,* an essential Japanese preparation of skipjack tuna in which the fish is briefly boiled, fermented with a mold, cold-smoked, then fully dried.

Smoke has natural antioxidants that offset the tendency of salt to accelerate oxidation and rancidity in cured foods.

Smoking in desert climes, such as the American Southwest, is often best done in the evening or at night. The air is so dry during the heat of the day that it makes it extremely difficult to raise the humidity in the smoker enough. At night, the humidity naturally rises as the desert cools, making it easier to smoke at high humidity.

CONTROVERSIES

Myths and Lore of Smoking

Of all traditional cooking techniques, smoking has perhaps the most ardent practitioners, who profess the most elaborate belief systems. Maybe that's because the process of smoking is somehow inherently mysterious and ritualistic. Or maybe it's because most cooks don't understand the scientific facts behind smoking. We don't want to appear irreverent, but we feel compelled to point out some cherished precepts of smoking that simply aren't true or are widely misunderstood.

Myth: The smoke ring adds flavor.

The smoke ring results from reactions between a protein molecule in red meat called **myoglobin** and the gases nitrous oxide and carbon monoxide in smoke. The product of those reactions can be seen but not tasted. The reactions do, however, prevent rancid flavors from developing, and they also stabilize the color of the myoglobin to an attractive pink hue that persists during and after cooking.

Myth: Soaking wood in flavorful liquids contributes to the taste of the food.

Most of these liquids react when heated to form vapors with an entirely different composition than the liquid. By dousing your wood with them, all you're really doing is lowering the smoldering temperature of the wood—and likely damaging the quality of the smoke.

Myth: Only solid chunks of wood generate quality smoke; sawdust or pellets won't work.

Pellets and sawdust are perfectly respectable materials for smoking, but the people who use them often close the flue too much, thus starving their smolders of oxygen—a practice that will, indeed, create poor-quality smoke.

Myth: Membranes on food block flavor penetration.

No, they don't. Biological membranes can block some liquids, but vapors pass right through them and dissolve into the moist flesh beneath. There seem to be two schools of thought on whether to remove the membrane from pork ribs: some swear it is essential to take it off, even as others are equally adamant about leaving it on. The reality is that this is a simple matter of personal preference. The membrane will not stop smoke or flavor from penetrating.

Myth: Only raw food absorbs flavor.

As long as the surface of the food stays moist, aromatic vapors will continue to adsorb there and diffuse into the food. In fact, we've had great success cooking food sous vide before smoking it. This misconception probably arose because of case hardening, an unfortunate consequence of poor technique in which smoking food develops a dry, hardened pellicle that *does* block flavor penetration.

Myth: Tars and oil droplets in the smoke create the pellicle and color the food.

Actually, like flavor, the color of smoked food comes from reactions with the invisible components of smoke—the gaseous volatiles—rather than the smoke you can see, which is a combination of liquid droplets and sooty solids. The gloss and shine of a great pellicle comes from a combination of resins that form when carbonyls and phenols in the vapor interact with proteins, sugars, and starches on the food surface.

Myth: Fat is essential for good smoked flavor.

There is some truth to this assertion. The fat content of meats and seafood dramatically impacts how well food absorbs flavor from smoke vapors. Flavorful phenols in the smoke vapor adhere most readily to fatty tissue, and, as a result, the fat in food accumulates aromas that would otherwise be greatly diminished in or even missing from the food. But too much fat covering the surface of meat actually prevents these flavors from diffusing into the flesh itself.

These pork spare ribs are in the early stage of hot-smoking, when neither the pellicle nor the smoke flavor has had time to develop fully. Hot-smoking works well for meat because the high temperatures and elevated humidity tenderize tough cuts by melting and dissolving collagen fibers.

SMOKING EQUIPMENT

Contemporary smoking equipment comes in a wide range of styles and prices. Although many designs use traditional methods of smoking food, at least one—the Handheld Smoker—was inspired by an entirely different kind of smoking. Not all systems are capable of true smoking or of the long smoking times at low temperatures that barbecue demands. A Traeger pellet smoker or a Bradley makes a great entry-level appliance for the barbecuer.

Stove-top smokers work fine for lightly seasoning pork chops or fish. And handheld smokers cater to the trend among cooks to capture smoke in a bell jar, then place it over the food during service, as a garnish. But if you're planning to make smoked food the centerpiece of a restaurant menu, you might want to invest in a commercial smoker such as the Enviro-Pak.

Custom-built smoker (right)

Price: varies widely

Pros: sizes range from backyard units for the home enthusiast to catering units for big parties; very good for traditional closed-pit smoking

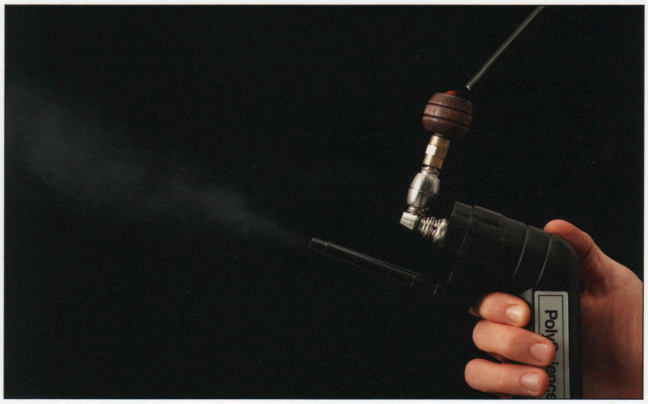
Cons: affords only limited control of the smoldering temperature and humidity; requires considerable skill and practice to operate

Stove-top smoker

Price: inexpensive

Pros: convenient and easy to use; suitable for light smoking

Cons: cannot easily generate high-quality smoke; not suitable for cold-smoking or lengthy hot-smoking



Handheld smoker

Price: inexpensive

Pros: supplies smoke for a visual and aromatic garnish; suitable for very lightly smoking foods

Cons: not capable of true smoking

Pellet smoker

Price: varies by model

Pros: pellet-fueled; suitable for cold- and hot-smoking; digital control available

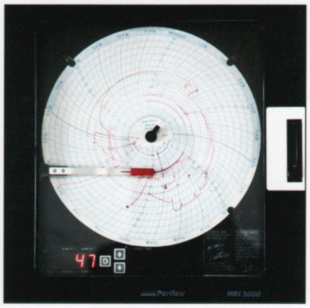
Cons: affords only limited control of the smoldering temperature and humidity; most models cannot perform cold-smoking below ambient temperature

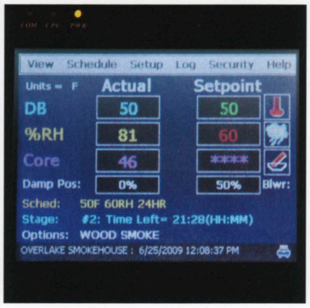
Bradley smoker

Price: moderately expensive

Pros: provides reasonable temperature control in the smoking chamber; good for cold- and hot-smoking

Cons: provides only modest control of the smoldering temperature; cannot perform cold-smoking below ambient temperature





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Enviro-Pak smoker

Price: very expensive

Pros: a computer controls the smoldering temperature, as well as the temperature, volume and humidity of the smoke entering the chamber with high accuracy; allows sophisticated programming

Cons: large and expensive; requires complex installation

Unlike the smoke from smoldering wood, smoke from burning wood is naturally humid because water vapor is the main product of combustion.

The bursts of smoke used in progressive smoking aid the penetration of flavorful compounds better than continuous smoking does. Continuous smoking can create an excessively thick surface film that prevents adhered molecules from diffusing into the food interior.

For more on cooking with combi ovens and water-vapor ovens, see chapter 8 on Cooking in Modern Ovens, page 150. For more on cooking sous vide, see chapter 9, page 192.

may cook and smoke for up to 24 hours, with the smoke fed from open fires that burn logs of wood. The smoke from open flames is humid, which helps to keep the surface of the meat from drying too much. Premier Texas barbecue joints such as Kreuz Market and Smitty's Market shunt the humid smoke from the open fire into a smoking chamber.

Other American barbecuers hot-smoke with smoldering wood. Although humidity is ample at first as steam wafts from the food, long smoking sessions require supplemental moisture from water-filled pans or spritzes from water bottles—or from basting with wet mops, glazes, or sauces.

Smoking Progress

German sausage makers have a more high-tech approach to humidity control during hot-smoking. Called progressive smoking, the process was created to make it easier to strip the casings from smoked sausages, but it has impressive advantages for all other kinds of hot-smoked foods.

As the name implies, progressive smoking is performed in stages. First you cook the food at high humidity to the desired core temperature. Then a brief period at low humidity dries the surface, which initiates the formation of the pellicle. Next the food is smoked in humid air for 20 minutes to several hours, depending on the size of the food. To get a strong but balanced smoke flavor, advocates of this method recommend smoking in 20-minute rounds, separated by five-minute pauses, for as many rounds as are needed.

Finally, the smoking stops, and the food cooks in hot, dry air just long enough for the color and surface texture to finish developing. Although any smoker can accomplish the smoking steps easily enough, the cooking and drying steps work best in a combi oven or a water-vapor oven, which both offer greater humidity control.

The advantage of progressive smoking is that it separates the drying and smoking stages, which maximizes the retention of juices and oils. The food stays moister and thus absorbs flavorful vapors better. Controlled studies have shown that progressive smoking produces better appearance, aroma, and bacteriological control.

If this technique seems unorthodox to you, we have an even more heretical suggestion. We advocate smoking food cooked sous vide—that is, with the food vacuum-sealed in a plastic bag, then cooked in a water bath. Cook the food sous vide as long as you like, remove it from the bag, and dry the surface in a standard oven at a low temperature until it is just tacky. Then smoke it in a humid environment (ideally around 80% relative humidity) until the smoked appearance and flavor develop fully. Depending on the desired degree of smokiness and color, this stage can be as brief as 30 minutes or as long as a couple of hours.

THE CHEMISTRY OF

What's in the Bottle?

Liquid smoke gained popularity in the 1960s and 1970s as an answer to concerns about carcinogens in smoked food. It also solved a public relations problem for smoked-food processors, whose habit of pouring pollution into the skies was becoming increasingly unpopular with the locals.

Chemists found it surprisingly easy to separate the aromatic fraction of smoke from the toxic compounds. The end result can have a wide variety of aromas and characters. Vendors, such as Wisconsin-based Red Arrow International, offer hickory, applewood, cherry, oak, beech, and mesquite selections, among others, in variations that include low-acid, high-browning, tarry, and sweet versions.

The production of all these diverse smoky flavors begins as real smoke made from real wood. Manufacturers of the best liquid smokes fine-tune their high-tech smoke generators to control both the temperature of the smoldering wood and the flow of oxygen to it with exquisite precision.

The smoke flows through an adsorption column that captures it in a fashion quite similar to the way that food does inside a smoker. A wash of water collects the adsorbed compounds in a tank, where the smoky water sits for weeks. Gradually, tars, resins, creosotes, and carcinogens settle to the bottom of the tank.

Those nasty by-products are discarded, and the good smoky water is filtered several times, then checked for quality and consistency. Manufacturers sometimes add back small amounts of water-insoluble tars and creosotes to impart some of the ashy and creosote flavors whose absence would otherwise be noticeable. A small amount of alcohol or a surfactant emulsifies these insoluble ingredients into the condensate. By controlling the smolder, the wash, and the mix of water-insoluble compounds, a manufacturer can adjust the flavoring and coloring qualities of liquid smoke with much greater precision than is possible with an artisanal smoker.

Once made, the smoke condensate can be sold at full strength, diluted with more water, blended into oil, or even made into a powder. Undiluted smoke condensate is typically revaporized to smoke foods during cooking. This strategy requires specialized equipment, but many industry experts feel it produces the highest-quality result.

Another more common and less expensive strategy simply drenches food with smoke condensates. Although lower-tech, this approach still requires care. Smoke condensate suitable for drenching always includes an emulsifier so that the condensate can be diluted to 20%–40% strength in water before being applied to the food. The surface of the food must dry enough to be tacky to the touch, but it still must essentially be raw.

Dripping the prepared food into smoke condensate for 45–60 seconds imparts enough liquid to do the job. But you'll get nice coloring and smoky flavor only if you finish with a cooking step that heats and slowly dries the surface so the condensate fully reacts. If you skip this step and submerge the food in liquid or cook it in a very humid environment, expect to see little surface color. The smoke flavor will also be acrid because the sour-tasting carbonyls can only react with proteins in the food when the food is neither too wet nor too dry.

Thus, just as with traditional smoking, a good drying step is an essential part of cooking with liquid smoke. As the food dries, you'll see the color develop; reactions between carbonyls from the smoke and proteins in the food brown the surface. When these reactions are complete, the acrid taste mellows, and the smoky flavor becomes more pronounced.

In practice, working with smoke condensates can be challenging, and good results can be difficult to achieve. Subtle details have a profound impact on the final result.

Very dilute liquid smokes, like those available in supermarkets, have condensate concentrations of 3% or less. These are useful mostly as flavorings to be added directly to food during preparation. Some versions add molasses or other sweeteners, whereas other products include vinegar as a less expensive way to lower pH without using high concentrations of acidic smoke condensate. These products are suitable for drenching food to achieve a very mild smoke color and flavor.

8

COOKING IN MODERN OVENS

COOKING IN MODERN OVENS

Culinary tools and implements have come a long way from ancient days when an open fire pit was the only place to cook. Ovens were among the first advances wrought by civilization; by 3200 B.C., every house in the settlements of the Indus Valley Civilization had its own clay oven. Early ovens were designed to trap the heat of a fire in the walls of the oven and divert the smoke away from the users, tasks that they performed well. By the early 20th century, inventors had developed gas and electric ovens that allow far greater control of heat and had done away with smoke entirely.

Yet for all the advanced features on today's ovens—broilers, forced convection, self-cleaning cycles, and so on—they still operate on the principle that controlling heat is the most important aspect of cooking. It turns out, however, that heat is just one of two critical factors that determine how food cooks. The other is humidity: the water content of the air surrounding the food. *Humidity governs the temperature at which food actually cooks.* It is also crucial for the food surface texture—the crispy crust or lack thereof.

The ability to manipulate moisture, both outside the food as well as inside it, is the defining difference that set modern oven technology apart from earlier methods. Water-vapor ovens and combi ovens control the water content of the heated air, so they can preserve the moisture content of food; microwave ovens exploit the moisture content of food to heat it. Although the technologies are unrelated, they are both examples of modern approaches to one of history's most ancient cooking tools.

Some traditional cooks worry that these newer devices might somehow devalue their hard-won skills or could even do away with the need for those skills entirely. Water-vapor ovens, combi ovens, and microwave ovens do circumvent, or even render obsolete, certain standard cooking techniques. But like most tools, a modern oven performs only as well as its operator understands it. The devices cannot exceed or replace the skills of the practiced cook; they can only help to better achieve the results the cook intends.

Racks of vacuum-packed carrots steaming in a combi oven (left) and roasting hams (right) highlight the versatility and large capacity of modern ovens. Roast chicken (opening photo) is one of the iconic foods prepared best by combi ovens. The ovens can produce a crispy, golden-brown skin on many birds simultaneously. To see how the ham turned out in the end, see page 101.

COOKING WITH MOIST AIR

Cooks have long understood the importance of keeping food humidified while it is heating. Moisture control is the reason they wrap baked potatoes in foil, cover casserole dishes, roast in bags, and braise and baste. Trapping the water vapor from cooking food is a crucial element of cooking sous vide as well (see chapter 9, page 192).

Of course, the reason that cooks have had to devise all manner of techniques to counteract the drying effects of hot air is that, until recently, they could not rely on existing equipment to do it for them. That situation changed a few decades ago, when engineers set out to develop improved food-holding cabinets and ovens for catering, institutional service, and fast-food vending. These innovators introduced two separate but related technologies to control, more precisely, the moisture content of the hot air and, consequently, that of the cooking food.

For more on the basic physics of heat conduction, see Heat in Motion, page 1·277. For more on relative humidity, the heat released by condensation, and evaporative cooling, see Vaporization and Condensation, page 1·314.

One of these groundbreaking technologies was developed by Winston Shelton, a former General Electric engineer who, in the early 1970s, worked with "Colonel" Harland Sanders to design and manufacture the Collectramatic pressure fryer that became the standard cooker for the Kentucky Fried Chicken chain of restaurants (see page 120).

In the early 1980s, Shelton's Winston Industries introduced the CVap brand **water-vapor oven,** which cooks with heated water vapor as well as hot air (**CVap** is short for "controlled vapor"). A few years before that, in 1976, German engineers at the company that would later become Rational AG invented an appliance known as the **combi oven**—so named because it can cook with ambient air as an ordinary convection oven does, cook with injected steam, or do both in combination.

These advanced ovens, and the many variations that other manufacturers have created since, have their strengths and weaknesses, but overall, they have proved to be extremely useful kitchen tools. You can use these modern ovens quite successfully for proofing, thawing, holding, roasting, baking, steaming, poaching, and—in the case of the combi oven—"oven frying." Their exceptional versatility means that these devices can provide most of the functions of convection ovens, steamers, holding cabinets, and grills—all in a single unit.

Steam burns hurt so badly precisely because the condensing steam passes so much heat into the skin. In that case, your skin is below the dew point temperature of the steam.

Along with greater control over the cooking environment and expanded cooking envelope come higher costs, particularly for the fully featured models. CVaps are less complex and priced more modestly. But like combi ovens, water-vapor ovens demand considerable time and effort to master—it takes a practiced operator to make the most of them.

Whether high-tech ovens are worth the expense and effort depends primarily on how well you learn to use them. It is helpful to first review the underlying physics of how heat interacts with moisture in the air, because that is fundamental to how these appliances work.

Air gains and loses heat much more readily than water (especially liquid water) does. A small alteration in the power output of a heating element in an oven therefore causes a much greater temperature change than does the same power rise in the heating element of a water bath. Although air temperature responds rapidly to the application of heat, it conducts heat poorly.

Heat transfer from air to food is much more efficient when water vapor is condensing onto cooler food than it is when hot air is simply convecting around the food (see It Matters How You Heat, page 1·283). The net result of all these factors is that an oven filled with dry air heats food quite slowly compared to an oven containing humid air. Moist air also smooths out temperature swings in the food and helps minimize hot and cold spots.

There is, however, a limit to how much water vapor air can hold before the water condenses into fog or dew. All else being equal, the hotter the air, the more water it can hold. The weather-report metric known as **relative humidity** describes how close the air is to its maximum water-carrying capacity at any given temperature.

Virtually all air contains water, and the relative humidity of air striking a cool object can soar to 100%. This is the process that makes a chilled bottle of wine "sweat" on a humid summer day and that deposits drops of dew on grass on a cold night. Indeed, the temperature at which the water vapor in a given volume of air starts to condense to liquid droplets is called the **dew point.**

If food is placed in moist air, and if the temperature of the food is below the dew point of that air, droplets of water will form on the food. This condensation releases a remarkable amount of heat energy, which tends to heat the food rapidly up to the dew point temperature.

Conversely, evaporating water *absorbs* a great deal of heat and hence cools food. In dry air, therefore, the heating of food will be offset by the cooling caused by water evaporating from the food surface. Because of **evaporative cooling**, the temperature that food encounters in an oven is rarely as high as that of the surrounding hot air. Instead, food cooks for most of the time at what scientists call the **wet-bulb temperature**, the temperature measured by a wet thermometer.

The more common temperature measurement is the **dry-bulb temperature**, which is the temperature that you measure with an ordinary thermometer that you keep shielded from direct sunlight and contact with moisture. The dry-bulb temperature is the one that you use when you set the temperature of an ordinary oven.

Unless the relative humidity is 100%, the wet-bulb temperature is always lower than the dry-bulb temperature. Food contains so much water that most foods spend the majority of their time with their surface at the wet-bulb temperature.

Cooking à la Mode

Engineers designed water-vapor ovens and combi ovens to give cooks better control over the all-important wet-bulb temperature. These ovens operate in several modes that are distinguished by the amount of humidity they employ. To use them effectively, you need to understand the differences among the various modes.

The **low-temperature steam mode** cooks food with air that has been saturated to 100% relative humidity, which means that the wet-bulb and dry-bulb temperatures are the same. "Low" temperature means heat levels below the boiling point of water, or 100 °C / 212 °F (at sea level).

Low-temperature steam mode is the same cooking environment as that found inside a sous vide bag or a covered pot. As water evaporates from the food, it is trapped by the sous vide bag, so the relative humidity quickly becomes 100% and further evaporation stops. The same thing happens in any covered container, such as a pot or a canning jar.

Low-temperature steam mode can be used to achieve the same effect without having a sealed container. In that case, the moisture to maintain the humidity comes from the oven, rather than just from the food. This approach shines when cooks want to achieve effects similar to sous vide with molded foods, such as flan or crème brûlée, whose shape would be destroyed by vacuum packing. It is also useful for slow-cooking large roasts or turkeys that are too big to fit inside a sous vide bag.

Another advantage of using low-temperature steam mode is that it effectively increases the cooking capacity, as reflected by the amount of heating power available. Water baths are typically limited to 1.8 kW, so they can't heat large amounts of food quickly. But even the smallest combi oven draws 10 kW of power, and CVap ovens draw a minimum of 5 kW.

The main disadvantage of using low-temperature steam mode as an alternative to cooking in a water bath is that the temperature control may not be as accurate, particularly for temperatures below 60 °C / 140 °F.

In **steam mode**, the relative humidity is also 100%, but the temperature is held exactly at the

For more on wet-bulb and dry-bulb temperatures and their significance to cooking, see The Real Baking Temperature, page 103.

Although it is something of a misnomer to call water vapor that has a temperature below water's boiling point "steam," the term "low-temperature steam" is so commonly used by oven makers that it has become standard terminology.

Fog pours from the open door of a combi oven that has raised the humidity of the cooking environment by injecting steam. Humidity control is a defining feature of modern ovens.

Manufacturers have chosen to sidestep the key concepts of wet-bulb and dry-bulb temperatures, perhaps in the belief that the prospect of cooking at two different temperatures simultaneously would flummox many cooks. Instead, their owner manuals talk vaguely about "doneness," "browning," and "humidity," terms that only obscure the relevant parameters. The table of cooking strategies on page 170 shows the settings on two popular modern oven models. Note that actual results vary with the brand.

boiling point of water (typically near 100 °C / 212 °F). Only combi ovens support this mode, which is no different, in principle, than steaming in a pot; it's just much more convenient and can handle larger quantities of food.

Some manufacturers use the term **convection steaming** for the steam mode, because their ovens use fan-assisted convection to circulate the air and water vapor over the surface of the food, a feature that hastens heating. Steam mode is useful for vegetables and other plant-based foods, which need the high heat of steaming. Most meat will overcook at steam temperatures if used for equilibrium cooking, which we describe below, but there are some cases in which it is useful.

Combi oven makers often advertise that their units' steam mode will reach temperatures as high as 130 °C / 266 °F, which falls within the range attained by pressure cookers. Although the dry-bulb temperature of the oven will indeed reach 130 °C / 266 °F, the all-important wet-bulb temperature cannot exceed 100 °C / 212 °F without applying pressure. The only way to steam food at higher temperatures is with a pressure cooker.

CVap and combi ovens also have a mode in which the wet-bulb and dry-bulb temperatures can be different, which is called **humidity-controlled mode, combination mode,** or **combi mode.** This approach to cooking can do things that no other kitchen appliance function can. Humidity-controlled mode lets you specify the

THE TESTING OF

Heat and Humidity Control in Modern Ovens

Combi ovens offer far greater control of temperature than conventional ovens do, and they allow you to control the humidity, too—but, unfortunately, not as well as we'd like. Our experiments show that the dry-bulb and wet-bulb temperatures in these ovens tend to fluctuate by several degrees around the set point.

These graphs show the actual wet-bulb (blue) and dry-bulb (red) temperatures for an empty Rational SelfCooking Center combi oven in steam mode, right after it was temperature-calibrated by a factory-authorized technician. The top left graph shows how a cold oven heats to reach its set point (30 °C / 86° F, in this case). Each subsequent graph, when read in rows from left to right, shows how the oven heated from the ending temperature in the previous graph to a new set point, indicated by the gray line.

Below 60 °C / 140 °F, both temperatures depart widely from the set point. This is why we hesitate to recommend combi ovens for cooking fish, rare meat, or other foods where you might need temperature accuracy. A water bath is much better at controlling heat. The manufacturer of the Rational combi oven reminded us that it is hard to do accurate temperature control in an empty oven and suggested that the performance would be better with an oven full of cold food. That might be true, but it still points to a weakness in temperature-control performance. Also note that it takes more than 10 min for the wet-bulb temperature to stabilize in the oven—even at the lowest set point (top left graph).

For set points from 60–90 °C / 140–194 °F, the accuracy of the oven is quite good, and it gets up to temperature quickly (although, in each case, it need only warm by 10 °C / 18 °F). A cold oven would take longer to attain a set point. The oven also works well for true steaming, in which wet-bulb temperatures are close to the boiling point of water. Note that the actual wet-bulb temperature is just below the boiling point, which is typical of "steamers."

Above 100 °C / 212 °F (bottom right graph), the dry-bulb temperature continues to rise, but the wet-bulb temperature does not. As long as the outside of the food has moisture rapidly evaporating away, the cooking temperature will remain at this lower wet-bulb temperature, unless the air pressure is increased.

We performed our tests with electric ovens. In our experience, gas-fired combi ovens have even larger variations in temperature because the gas flame produces large pulses of heat as it turns on and off. We hope that manufacturers will design and build ovens that incorporate more accurate and precise temperature and humidity controls. A direct way to set wet-bulb temperature is also a needed feature (see Ways to Make Modern Ovens Better, page 167).

In combi and convection mode, the dry-bulb temperature results are similar to what is shown at right for steam mode: a cold oven takes about 10 min to come up to temperature—5 min or less if the oven is already hot. The wet-bulb temperature is much more variable than in steam mode; the humidity-control mechanisms have limitations at these temperatures. These modes are still valuable features, but fine control of humidity does not seem to be possible with the combi ovens that we have tested.

temperature at which the food cooks by setting the wet-bulb temperature directly. At the same time, you can increase the dry-bulb temperature enough to dry and brown the food—a process that occurs only when the dry-bulb temperature substantially exceeds the wet-bulb temperature. In a conventional oven, only the dry-bulb temperature is under your control.

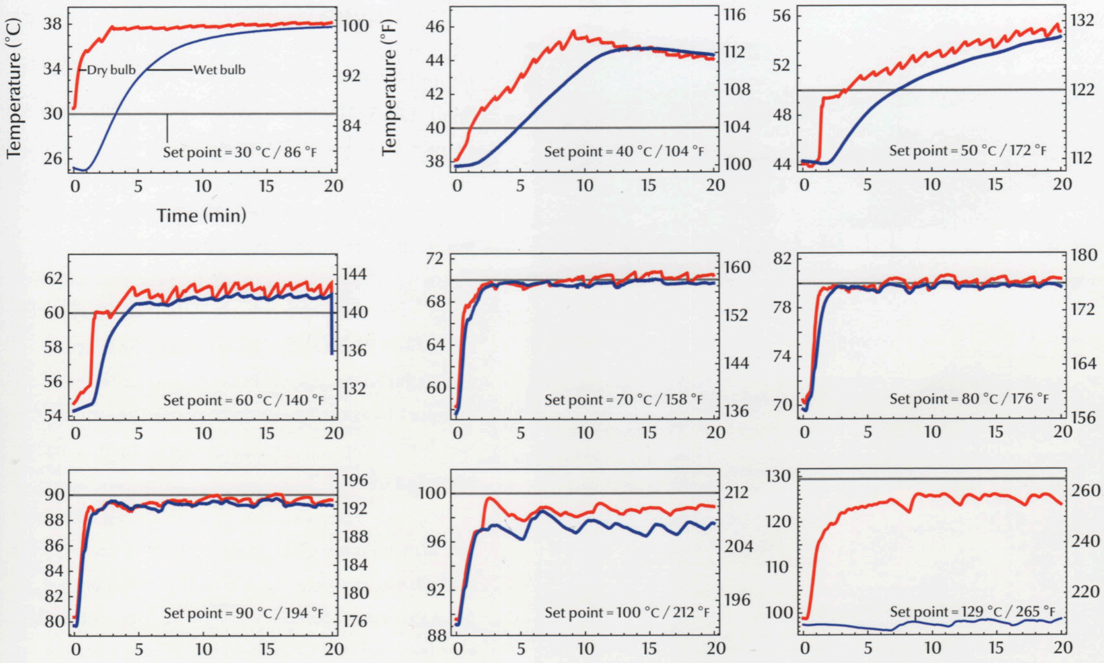
Combi ovens offer a **convection oven mode**; CVaps do not. In this mode, the combi oven performs like an ordinary convection oven, reaching temperatures up to 300 °C / 572 °F. Although a combi oven can often stand in for a conventional oven, light baking or delicate dishes are out because the force of the oven fan can blow a custard clear out of its ramekin. The fan can be set at half speed, low enough to cook some delicate foods. Alternatively, you can put delicate foods inside a very deep hotel pan or a stockpot to shield them from the full force of the convection fan.

The convection oven mode also offers humidity control but in one direction only: you can set the maximum humidity that the oven will allow. It will not add moisture to reach that level, but it will vent moist air from the oven in an attempt to prevent the humidity from exceeding that value.

To get the most out of these devices, you must experiment to understand the nature of the cooking processes they offer as well as your machine's specific options and limitations. Only with experience will you learn to best exploit their capabilities to prepare your favorite dishes.

Low-temperature steam mode on a combi oven or water-vapor oven can be used to cook food sous vide. Cooking foods in pans or on trays placed in such ovens yields results very similar to those of water baths, without the need for bags and vacuum-sealing.

The popularity of water-vapor ovens and combi ovens as tools for low-temperature steaming (without the need for vacuum-packing food) soared in New York City after the city health department cracked down on sous vide preparation (see page 1·188).



These graphs show the dry-bulb (red) and wet-bulb (blue) temperatures in a Rational SelfCooking Center combi oven that is in steam mode (see text at left). Our experiments were performed immediately after the oven was calibrated by a factory-authorized technician.

Dedicated steamers and convection steamers also exist and can take the role of steam mode, but they generally have no temperature control and only operate at the boiling point of water.

AccuTemp also makes the Accu-Steam Griddle, an advanced design that uses steam to heat the cooking surface. For more on using the Accu-Steam, see page 37.

Water-Vapor Ovens

The basic concept of the water-vapor oven is simple: heat a pan of water in the bottom of an oven enclosure to cause it to evaporate enough to raise the humidity of the air inside, thereby keeping more moisture in the cooking food. CVap inventor Winston Shelton figured out how to use this principle to hold prepared dishes for hours without drying them out. Previous holding equipment had improvised on this theme, using a supplementary water vessel to help retain the moisture in food (as steam tables do) or sealing the holding cabinet to prevent the escape of moisture (as the cook-and-hold equipment made by Alto-Shaam and others does).

But those designs allow cooks to control temperature and humidity only crudely. Shelton's oven, while not perfect, enables operators to manage the humidity much more definitively, partly because the CVap provides better temperature stability than any ordinary oven or holding cabinet does.

Another vapor oven, the Steam'N'Hold unit from Indiana-based company AccuTemp Products, works by creating a partial vacuum that reduces the air pressure until the boiling point of water equals the temperature that the cook selects for steaming. Consequently, the Steam'N'Hold can function only in steam mode or low-temperature steam mode. The CVap oven is more versatile, so we will discuss that brand in detail.

The CVap oven contains both a resistance heating element in a pan of water at the bottom and other heating elements on the sides (see Not Just Hot Air, page 160). It has two kinds of controls, typically labeled "Doneness" and "Browning" ("Food Temperature" and "Food Texture" on older models), which control the two respective sets of wet and dry heating elements and thus the oven's wet-bulb and dry-bulb cooking temperatures.

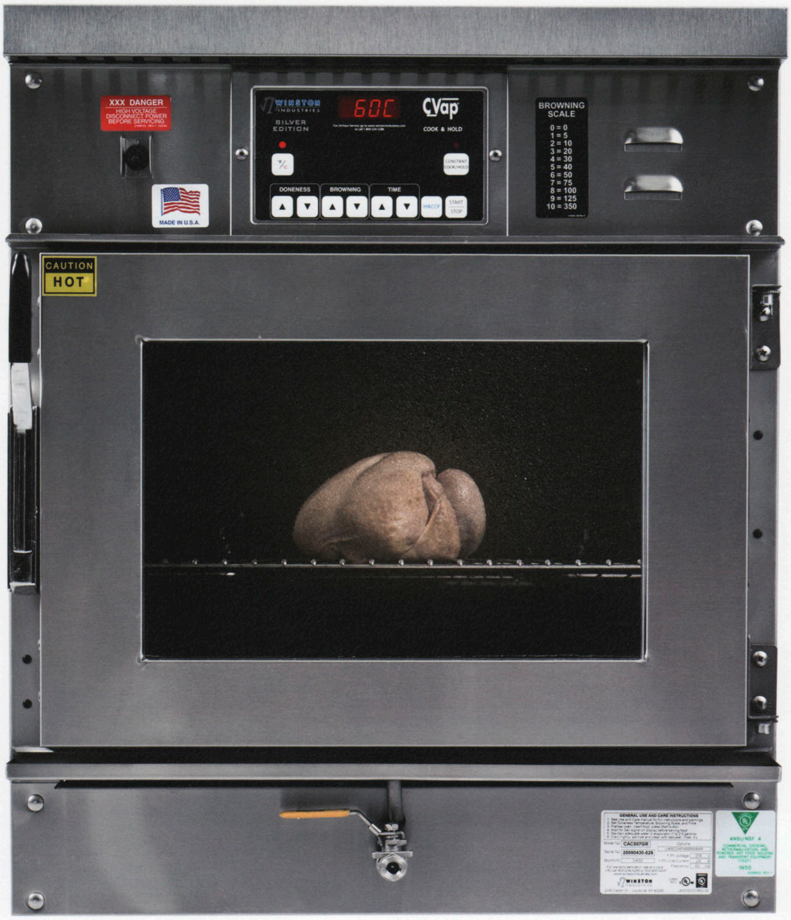
The Doneness setting allows cooks to manipulate the wet-bulb temperature by setting the temperature of the water at the bottom of the machine. As the water warms, it vaporizes into the oven air. When the preheating process is complete, both the water vapor and the air will be at the same temperature as the water in the pan—the wet-bulb temperature.

Using this setting is much like controlling the temperature of a water bath, and, like a water bath, the CVap takes a long time to heat up. In our experience, you should set aside about 45 minutes to allow the oven to reach the proper wet-bulb temperature, assuming it starts at room temperature.

Because water can absorb considerable heat, any temperature change in a CVap or a water bath takes time, too. The upside to this delay is that, once the target temperature is reached, it fluctuates less and hews closer to its set point than a combi oven does: typically staying within 1–5 °C / 2–9 °F. That is still not as precise as a water bath but is sufficient for most culinary applications.

Unlike the Doneness setting, which is scaled according to temperature, the Browning control is demarcated by numbers that run from 0–10 and represent power levels. We feel that this arbitrary 0–10 scale hinders rather than helps. Knowledgeable users would strongly prefer to set

A chicken bakes in a CVap oven, where it both cooks in moist heat and browns slowly in a single step.



the dry-bulb temperature directly, but that option is not yet available.

If you dial the Browning meter to zero, the heating elements on the sides of the oven do not energize, and the temperature of the oven air will be the wet-bulb temperature. Running the CVap with Browning at zero is the closest equivalent that the CVap has to low-temperature steam mode. The relative humidity of the air in the oven will be at or close to 100%, so the food surface will not dry out, nor will browning occur. Use this setting either to cook sous vide in a CVap or to get sous vide-like results in an open pan.

CVap users also value the low-temperature steam mode for holding fully cooked food relatively intact, thus keeping dishes warm for hours without drying them out, which was one of the target applications that drove the invention of the technology in the first place. Caterers know, however, that holding browned food items often causes streaking to occur. Moisture inevitably condenses on the surface of the food because it is cooler than the surrounding air, and the resulting droplets run.

You can prevent streaking by holding browned food at settings ranging from 1–4, which engages the side-mounted heating elements. This warming raises the dry-bulb temperature above the wet-bulb temperature, reducing condensation. At these low-to-moderate Browning levels, you need not worry about drying the food out completely.

Surprisingly, these settings permit you to hold crispy food such as fried chicken for long periods. Without the browning setting, the humid environment of the CVap would inevitably soften a crispy skin or crunchy crust, but a high dry-bulb setting compensates. You can hold eggs sunny-side up this way without ruining their delicate consistency.

At Browning settings 5–10, you can cook food and brown it at the same time. To bake chicken, for example, you can set the Doneness dial to 60 °C / 140 °F and the Browning control to eight or nine. At these higher settings of the Browning control, the CVap oven operates in what amounts to combi mode, where the wet-bulb temperature is controlled by the Doneness dial, and the dry-bulb temperature is set by the Browning control (albeit with no indication of the dry-bulb temperature).

Unfortunately, the wet-bulb and dry-bulb temperature settings in the CVap are not completely independent. The higher Browning settings inevitably cause the wet-bulb temperature to creep up as the warm oven air starts to heat the water in the pan. The oven could be designed to combat this effect, but that awaits future work. Consequently, at high Browning settings, the air inside the oven eventually gets too humid to dry the food surface, and the effective cooking temperature (the wet-bulb temperature) rises too high to get the best results with some foods.

In addition, the CVap approach to humidity control leads to a relatively narrow range of temperatures in which it can control the wet-bulb and dry-bulb temperatures independently. Even with Browning set to 10, the temperature will reach a maximum of only 180 °C / 356 °F, a rather modest oven temperature for browning. This limitation derives in part from the CVap's heritage as a holding-cabinet design.

Browning Level and Dry-bulb Temperature

Browning level	Dry-bulb minus wet-bulb temperature (°C)	(°F)
0	0	0
1	2.8	5
2	5.6	10
3	11.1	20
4	16.7	30
5	22.2	40
6	27.8	50
7	41.7	75
8	55.6	100
9	69.4	125
10*	see note below	

For browning levels 0–9, the dry-bulb temperature = the wet-bulb temperature (Doneness level) + the temperature difference given in the table above.

*At Browning level 10, the dry-bulb temperature is set to 180 °C / 356 °F regardless of the wet-bulb temperature.

Each Browning level has successively larger temperature differences to approximate a logarithmic scale.

We would prefer setting the dry-bulb temperature directly, but by using the table above, one can set it indirectly. You can calculate the dry-bulb temperature from the Browning level and wet-bulb (Doneness) temperature level.

CONTROVERSIES

Forced Convection in CVap Ovens

Winston Shelton, the inventor of the popular CVap oven and the Collectramatic pressure fryer, the classic cooker of KFC franchise fame, has strong opinions about forced convection in ovens, and none of them are positive. Shelton says that he put a fan in his CVap water-vapor oven only at the urging of marketing advisors, who maintained that customers would expect the oven to have a fan, whether or not it speeds heating or helps to deliver heat to food more evenly. If you ask him, it does neither.

Shelton says that any kind of convection is unlikely to hasten heating substantially in a water-vapor oven because the amount of thermal energy that is transferred to the food by the phase change when water vapor condenses far exceeds any extra heat transfer caused by circulating air.

Convection-oven advocates are "word spinners," Shelton charges: "marketers who need to 'featurize' their product to make more money on it." The truth, according to Shelton? "'Convection oven-ing' is hogwash."

NOT JUST HOT AIR

A controlled-vapor oven, or CVap, allows you to set the wet-bulb temperature directly. Because the wet-bulb temperature usually determines the effective cooking temperature, the CVap is a huge improvement over traditional ovens that control only dry-bulb temperature.

The wet-bulb setting controls the temperature of water in a reservoir at the unit's bottom, and vapor from the water tends to enforce that wet-bulb temperature in the oven air. You can set the dry-bulb temperature by using the "Browning" control.

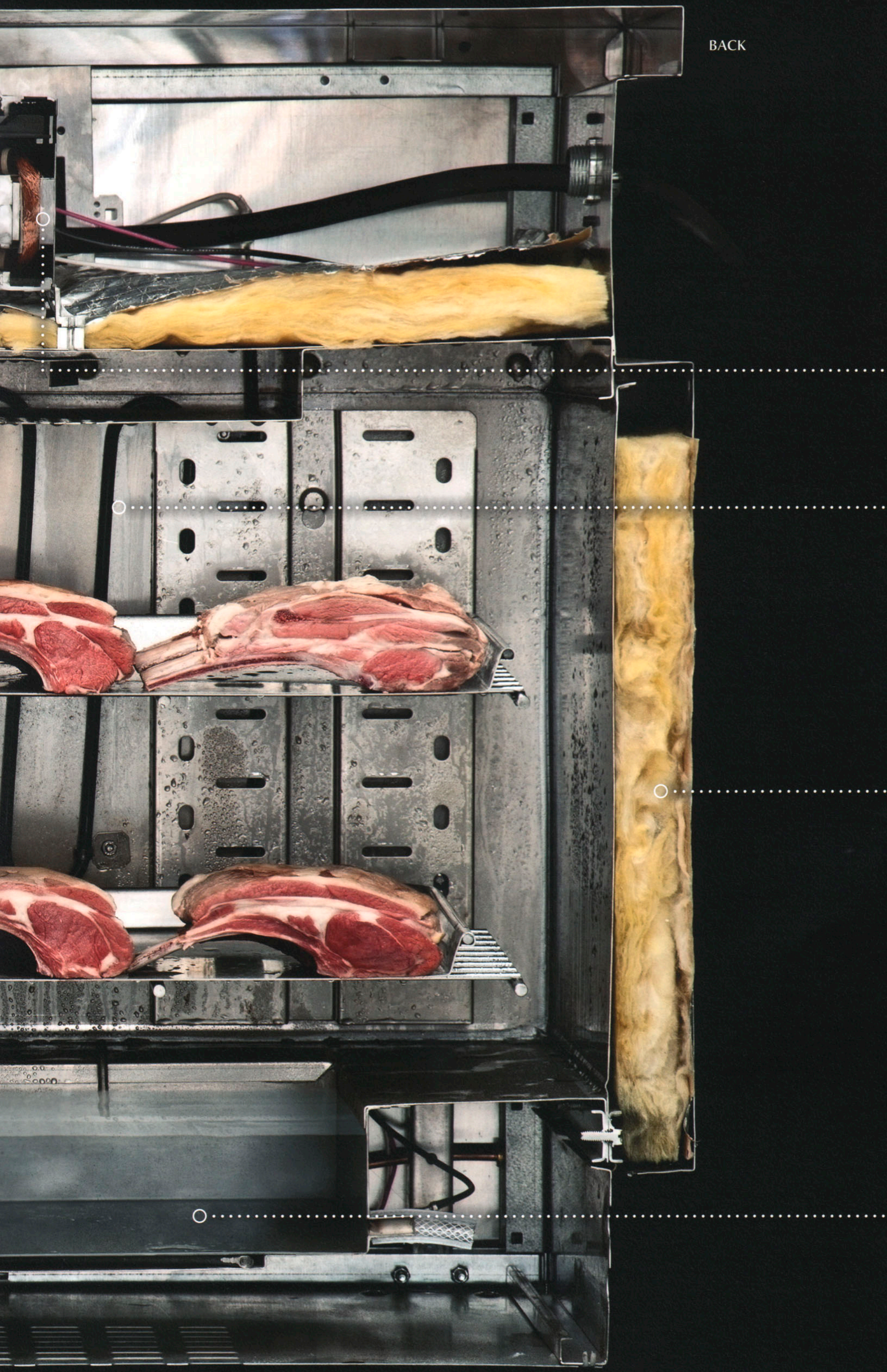
The CVap works well for cooking sous vide and for many other low-temperature cooking operations. It also makes a fine holding oven to maintain food at temperature and preserve its texture—its original purpose.

The digital control unit lets you specify the wet-bulb temperature directly, using the Doneness setting. You can set the dry-bulb temperature only indirectly, by specifying a Browning level from 0–10.

A double-pane glass door offers a clear view of the food as it cooks.

The drain tube captures water that condenses on the door and channels it to the water reservoir.

The drain valve makes it easy to empty the reservoir.



The fan motor drives blades that force convention currents to flow around the oven interior.

An electrical heating element warms the oven air separately to maintain the desired dry-bulb temperature.

Fiberglass insulation helps to hold heat inside the oven chamber.

This water reservoir, heated separately from the oven to the desired wet-bulb temperature, is fundamental to the way that the CVap maintains the wet-bulb temperature in the oven chamber.

As a result, the CVap browns food rather slowly and achieves only modest levels of browning. Although it is quite possible to achieve good results, such proficiency requires trial and error, and the oven simply may not be suitable for certain tasks.

Some chefs have developed recipes using the Doneness (wet-bulb) and Browning levels on a CVap to cook and brown certain foods perfectly in a single step. Developing such a recipe requires diligence and experimentation. Even then, their formulas work only within a certain range of foods, temperatures, and food sizes.

Although it's possible to cook and brown in a single step with the CVap, we would rather cook using a multistage process that first employs the oven's high heat source for searing and browning, then uses the CVap in low-temperature steam mode to finish the cooking. You could also do the reverse: low-temperature steam first, then sear. The multistage approach gives the cook greater control and works with a broad spectrum of foods. In essence, it is cooking sous vide without the vacuum packing.

For the price of one combi oven, you could purchase a couple of water baths, plus a convection oven and a broiler. Or you could get a water-vapor oven and a conventional convection oven. If you have the space, installing multiple tools yields the same functionality, but with the added benefit that you can use them simultaneously.

Combi Ovens

Many veteran chefs rate the combi oven as the most versatile kitchen tool ever made. Unlike the CVap, which relies on evaporation from a water reservoir to generate humidity, combi ovens supply moisture directly, by injecting steam into the semisealed oven chamber. The combi oven's ability to use both steam and circulating hot and dry air, either alone or in combination, can reproduce, in a single appliance, many cooking techniques: steaming, proofing, incubating, dehydrating, baking, grilling, frying, and more. Cooks can program combi ovens to automate routine tasks, and the machines are self-cleaning.

On the downside, a combi oven is not cheap: as of 2010, it costs roughly $12,000 for the half-sheet-pan-size programmable ovens we use—and several times that amount for larger configurations. Miniature combi ovens designed for commercial kitchens have recently come on the market for as little as $2,000, but these are limited to using much smaller pans. Manufacturers of kitchen equipment for the home have also started to show interest in combi ovens, so in the future, there will likely be many more options.

Combi ovens are also rather expensive to operate because they consume a lot of energy, at least when using those modes that employ high heat. And while their flexibility is unmatched, the fact remains that a single combi oven can do only one cooking task at a time. If you really want to fully exploit the versatility of these machines (and if you have the necessary budget and space), buying several small units rather than a single large one makes sense.

Seasoned cooks especially appreciate the combi oven's unprecedented ability to get consistent results in operating conditions that would otherwise cause fluctuations in the wet-bulb temperature—deviations that would ordinarily produce undesirable outcomes. Differing results can arise, for instance, from the change in cooking performance when an oven is full or only partially filled, or from the seasonal change in humidity between a dry winter morning and a muggy summer afternoon. Combi oven settings enforce, more or less, a steady regime of temperature and humidity that smooths out most variations.

Note that we say "more or less." Our experimental results (pictured in the graphs on page 157) reveal that temperatures in combi ovens do tend to wander a bit more than is ideal. That failing stems in part from their design. The ovens were developed in a context that did not put a premium on tempera-

The Rational combi oven was the first of its kind and is still a market leader. We base our discussion on this particular brand, but its features are similar to those of many other combi ovens.

ture accuracy, so this aspect of performance may not have been a high priority for the designers.

For example, we've seen temperatures fluctuate in our combi ovens because the fans reverse direction every four minutes. The reversal helps distribute heat more evenly, but it also causes momentary, local temperature blips in the oven. In our experience, the oven temperature tends to drift over time, and you need to calibrate combi ovens frequently if you want them to be accurate.

Out of the three Rational combi ovens that we have, one of them—admittedly, the oldest unit—has consistently had poor temperature performance despite repeated service calls. The humidity control on these machines is also rather wobbly, again as a result of their design and of intrinsic physical limitations. It is quite possible that the increasing focus on Modernist cooking and the accuracy it requires will drive manufacturers to improve temperature performance.

The other problem with combi ovens concerns their humidity settings, which are quite obscure—to the point where even experienced combi oven users and company personnel often have the wrong idea of what the settings mean. To explain the problem, we'll consider the Rational combi oven in detail. It was the first combi oven and remains a leading brand. Other combi ovens have similar issues, however.

Rational Humidity

The control panels of Rational combi ovens feature two buttons that operators find fairly straightforward to use: a blue one for moist heat (steam) and a red one for dry heat. When you hit either of the keys, a pane below the buttons illuminates with either blue or red bars that can be set from zero to 100.

Rational's user manual describes this action as setting "the exact percentage of humidity." That description might, however, lead operators to suppose that the scale corresponds to relative humidity, or the amount of water vapor in air expressed as a percentage of the air's total carrying capacity at that temperature. Indeed, some Rational employees told us just that. The trouble is that this interpretation cannot be accurate because *relative humidity loses any useful meaning at temperatures above the boiling point of water.*

The "exact percentage" that Rational refers to is in fact something more arcane, though in some ways more absolute. It measures the fraction of the total mass of air and water in the chamber that is water vapor. If a volume of air has no water in it, then the so-called Rational humidity is 0%.

Note that this 0% is purely a theoretical minimum that is impossible to achieve in practice because doing so would require perfectly dry air, which simply does not exist in Earth's atmosphere. The minimum humidity that the oven can produce depends on how much water is in the air of the kitchen—which can be quite a bit. In a working kitchen on an extremely muggy, blisteringly hot summer day, for example, relative humidity in the ambient air could be near 100%. The oven can add water (as steam), but it cannot remove water.

On the other hand, if the chamber contains only pure water vapor (steam) in the chamber, with no air at all in the oven, then the Rational humidity is 100%—another condition that could never occur in practice.

Regrettably, this explanation does not appear in the owner's manual for the unit; we had to extract it during detailed correspondence with the company's engineers (who were very helpful). Their reasoning makes sense: by inventing the concept of Rational humidity, the engineers created a scale that works at all temperatures, whereas relative humidity becomes completely unhelpful at temperatures above the boiling point of water.

Unfortunately, most of the Rational humidity scale is useless because it represents values of heat and humidity that the oven cannot attain, even in principle. At 30 °C / 86 °F (the lowest temperature setting on a Rational combi oven), the only valid Rational humidity settings are between 0% and 2.6%. Any setting above 2.6% *is impossible to achieve.* At 60 °C / 140 °F, a common cooking temperature, the valid range is 0%–13%. Even at 90 °C / 194 °F, the valid range runs only from 0%–58%.

Imagine cooking on the humid summer day described earlier, with outside temperatures around 40 °C / 104 °F and relative humidity near 100%. The minimum possible Rational humidity would be 4.6% (at any temperature). Setting the oven to 0% will not help.

On a very cold winter day, in contrast, you could get closer to the mark. If the outside temperature

Halibut fillets cook in a combi oven.

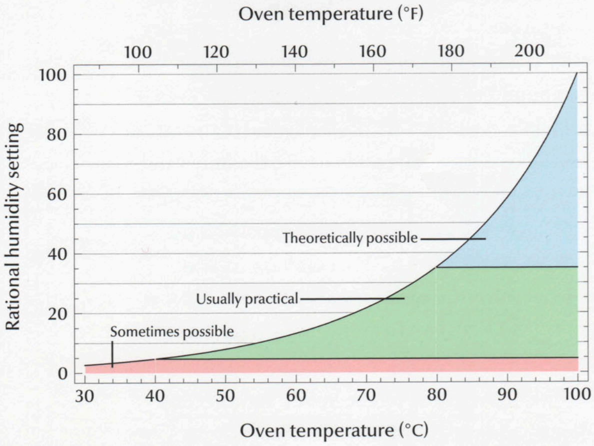
Combi ovens need to be calibrated regularly. Their temperature controls can be off even when they're brand-new, so have yours checked upon installation and check it again yourself at least once a year thereafter. Use a digital thermometer positioned in several places in the oven, and if you find the readings don't match one another or the machine's temperature setting, have a technician adjust the unit.

For the best results, control both temperature and humidity in your kitchen. This will improve the reliability of your combi oven but also has many other advantages because humidity affects almost every aspect of cooking.

is below 0 °C / 32 °F, and you bring the external air into the kitchen unchanged (without further humidification), you could get the oven to operate under conditions that correspond to 1% on the Rational humidity scale—but still not all the way to 0%.

A further limitation on the Rational humidity system is the fact that the food itself gives off water vapor as it heats, and that causes the humidity in the oven to rise. The oven can compensate for this effect somewhat by venting the humid air, then refilling with new kitchen air heated to the right level. But the compensating effect is limited by the electrical power available. The oven must recirculate at least some of the air; it does not have enough power to heat kitchen air all the way up to most oven temperatures, then dump it, the way a hair dryer does. The amount of air that the oven must recirculate depends on the temperature setting and the oven's power rating.

The practical consequences of these deficiencies is that, below 100 °C / 212 °F, you have only very crude control over humidity—not the sophisticated command suggested by the control panel. Realistically, you have only two settings to consider: 0% and 100%. Use 0% to dehydrate the food. Use 100% if you are performing low-temperature steaming, a process in which you want the dry-bulb and wet-bulb temperatures to be the same.



The Rational humidity setting spans 0%–100%, but most of that range is impossible to achieve at temperatures below the boiling point of water. The red zone indicates settings that can be achieved—but only when the kitchen-air is dry enough. The green zone denotes those settings that are practical for cooking under most circumstances. The blue range shows settings that the oven can achieve in theory but that are difficult to attain in practice and that would not significantly change cooking conditions in any case. All Rational humidity settings higher than those in the green range produce the same effect. Note that we assume sea level elevation, where boiling point is 100 °C / 212 °F; the curve would shift to the right at higher elevations, where the boiling point is lower.

One could argue that the 5% setting results in greater repeatability because at that setting, the Rational humidity will be the same whether it is a dry or moist day. This is true, but the oven's humidity controls do not seem to be accurate enough for that subtle point to matter.

The situation is a bit different when the oven gets to temperatures above the boiling point of water (100 °C / 212 °F at sea level, lower at higher elevations). At the high end of the scale, 100% Rational humidity then means that there is no air left in the oven at all; it is filled with pure steam. If the oven vented the combination of steam and condensed fog as fast as it could and replaced that combination with pure steam, it could make the Rational humidity very high. The oven is limited, however, by the heat capacity of its boiler (or, for some ovens, the capacity of the steam generator). It can only vent gases as fast as the steam generator can replace the steam-air mix with steam, and that rate is limited by the electrical power. So the oven will never replace all the air with steam.

In practice, a different limitation makes this insufficiency moot. The only practical reason to raise the humidity of an oven is to make the wet-bulb temperature approach the boiling point of water (100 °C / 212 °F at sea level). The wet-bulb temperature can never exceed the boiling point, even with 100% Rational humidity. And as the humidity rises, incremental increases in humidity make less and less of a difference to the wet-bulb temperature.

Even at a dry-bulb temperature of 300 °C / 572 °F, theory tells us that the wet-bulb temperature for 30% Rational humidity will be 81 °C / 178 °F. At 50%, it will be 89 °C / 192 °F, only a small improvement. Note that dry-bulb temperature is not much of a factor: at 100 °C / 212 °F, the wet-bulb temperature at 30% Rational humidity is 77 °C / 171 °F, and at 50%, it is 87 °C / 189 °F (again, this is from theoretical calculations). The wet-bulb temperature only changes by a few degrees as the dry bulb increases by 200 °C / 360 °F and also by only a few degrees as the humidity changes from 30% Rational humidity to 50% Rational humidity.

Meanwhile, our experimental data show that the wet-bulb temperature in a Rational fluctuates by 10 °C / 18 °F over the course of 10–20 minutes in even the best and most stable cases. So the reality is that, once the dry-bulb temperature is

above the boiling point, Rational humidity settings above, say, 40% do not differ from one another in any meaningful way.

At the low end of the humidity scale, another set of restrictions apply. The only way the oven can minimize humidity is by venting moist air from the oven and replacing it with kitchen air, which must first be heated to the proper temperature. The available power limits the rate at which the oven can generate this hot, dry air. The extent to which this becomes a limitation also depends on temperature. Heating ambient air to 60 °C / 140 °F takes less energy than heating it to 300 °C / 572 °F. Using a very low humidity setting (0%–10%) with high oven temperature is likely not to achieve what it ought to, but the oven will try its best to get there.

In our experience, in either convection mode or combi mode, you again basically have two choices: 0% and 100% Rational humidity. For dry-bulb temperatures below the boiling point, all dry-bulb temperatures produce the same wet-bulb temperature, which is about 45 °C / 113 °F but varies from 42–48 °C / 108–118 °F. Above the boiling point, all dry-bulb temperatures produce the same wet-bulb temperature of about 67 °C / 153 °F, which varies from 64–72 °C / 147–162 °F.

At Rational humidity of 30% or greater, the results at dry-bulb temperatures below the boiling point are basically the same as for 0% Rational humidity. That's because the range of possible Rational humidity is restricted—and because the controls are just not that accurate. Again, the wet-bulb temperature is about 45 °C / 113 °F, with a similar range. Dry-bulb temperatures above the boiling point produce a wet-bulb temperature of about 84 °C / 183 °F, which varies from 80–86 °C / 176–187 °F.

Note, however, that these results are all approximate: your oven's performance may vary. Note also that these results are from sea level; you can expect somewhat different results from combi ovens located at higher elevations.

All this criticism may leave the impression that the humidity control on the Rational combi oven is a bad thing. Quite the contrary: humidity control on combi ovens is a great feature that you

It is much harder to set the wet-bulb temperature in a combi oven than in a CVap oven. At temperatures below the boiling point of water, the wet-bulb and dry-bulb temperatures are the same inside the oven. Above the boiling point, the wet-bulb temperature is, in principle, a complicated mathematical function of the humidity, dry-bulb temperature, and fan speed. But we found that, in practice, the empirical oven results do not match the results of the calculations very well.

Effective Cooking Temperatures in a Rational Combi Oven

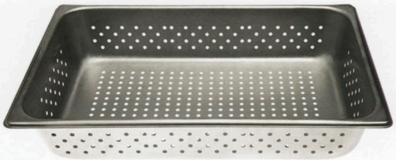
In the four cooking modes offered by a Rational cooking oven, the effective cooking temperature (the wet-bulb temperature) depends on both the dry-bulb temperature that has been set as well as the Rational humidity setting. The table below shows the ranges of wet-bulb temperature that are accessible in each mode.

Mode	Dry-bulb temperature setting		Rational humidity	Wet-bulb temperature actually achieved		Note
	(°C)	(°F)		(°C)	(°F)	
low-temperature steam	30–60	86–140	100%	same as dry bulb		poor temperature control
	60–90	140–194				good temperature control
steam	100–129	212–264	100%	98 (96–99)	208 (205–210)	good temperature control
convection	30–100	86–212	0%	45 (42–48)	113 (108–118)	useful primarily for dehydration or for dehydration and cooking combined
			≥limit	42–88	108–190	poor control of wet-bulb temperature, which varies with oven load and moistness of food
	100–300	212–572	0%	80–88	176–190	oven keeps humidity as low as it can; best regime for browning
			≥30%			poor control of wet-bulb temperature, which varies with oven load and moistness of food
combi	30–100	86–212	0%	45 (42–48)	113 (108–118)	functions just like convection mode
	30–60	86–140	≥maximum*	same as dry bulb		poor temperature control
	60–90	140–194				good temperature control
	100–300	212–572	≥30%	84 (80–88)	183 (176–190)	more reliable than convection mode because moisture is added

*Maximum Rational humidity in combi mode depends on the dry-bulb temperature setting. It is 2.6% at 30 °C / 86 °F and 58% at 90 °C / 194 °F. Note that Rational humidity settings above 50% are difficult for the oven to achieve in practice.

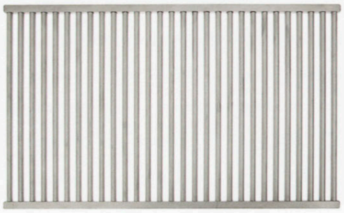
A PANOPLY OF PANS

Combi ovens call for a range of accessories to accommodate their many uses. The various pans used in combi ovens testify to just how versatile these appliances can be. Some of these pieces, such as the hotel pans, are standard-issue essentials; other pans are more specialized.

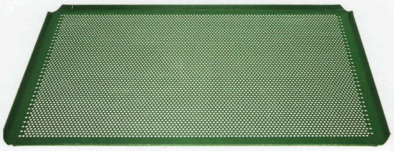


Perforated hotel pan, or "steamer pan"
Depths range from 1–20 cm / ½–8 in

Hotel pan
Available with or without Teflon coating and in one-half and one-third sizes



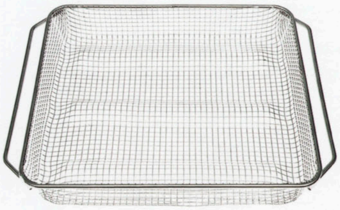
Combi grill
Marks food, just as a conventional grill does



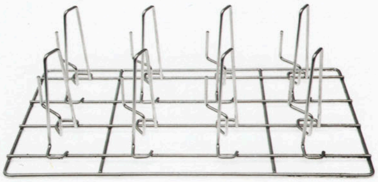
Perforated baking sheet
Holes in the nonstick sheet help the bottom of bread to bake rather than steam

Enameled pan
Coating withstands high heat and can produce searing effects

Poached-egg pan
Indented and coated with Teflon for easy removal



Wire basket
Allows full access to hot air for simulated frying



Chicken rack
Holds birds upright for optimum crisping; a duck rack is also available

Pizza stone
A custom-made sheet of thick metal for baking pizza pies

can use to make terrific food. There is just plenty of room to improve the current technology with a different interface and approach.

Cooking in a Combi

Fortunately, a cook need not know the precise wet-bulb temperature in a combi oven to get fantastic results (see the table of cooking strategies on page 170). We have favorite applications for these ovens when they operate in several different modes.

Low-temperature steaming, for instance, works very well in combi ovens, especially at temperatures of 60 °C / 140 °F and higher. Set the unit to steam mode with humidity at 100% and the temperature anywhere between 30–100 °C / 86–212 °F. This mode excels for poultry, meats, and all manner of plant foods. Conventional steaming at 100 °C / 212 °F works well, too.

The advantage of the combi oven, when used this way, is its capacity: how else can you steam 4.5 kg / 10 lb of broccoli or prepare a hotel pan of rice? Caterers often rely on combi ovens to steam in bulk, and they also take advantage of the speed of the devices; combi ovens come up to temperature within 5–10 minutes and cook far faster than either a water bath or a CVap does.

In our experience, however, combi ovens are not particularly adept at holding temperatures below 60 °C / 140 °F. We've used them to cook fish, which we most often prefer steamed at 45 °C / 113 °F, and to prepare steaks, which we like rare to medium rare (50–55 °C / 122–131 °F). The **equilibrium cooking** approach, similar to that used for sous vide (see page 243), is to set the oven to a temperature 1 °C / 2 °F above the desired core temperature. Unfortunately, the temperature in a combi oven varies so much at temperatures this low that a water bath is a much better place to cook fish and red meat.

To circumvent this shortcoming, you can adopt a "hotter-than-core" cooking approach (see page 245) with the combi oven set at 60 °C / 140 °F, the lowest temperature at which it seems to provide reasonably accurate and precise performance. The risk with this approach is overcooking the food. Even when the core is cooked perfectly, some

Large roasts can be successfully cooked to rare temperatures in a combi oven. Even though the temperature is not perfectly accurate, the fluctuations tend to average out when a large piece of meat is cooked over a long period of time. Smaller food pieces with shorter cooking times are more problematic. The shorter the cooking time, the more important the fluctuations become.

INNOVATIONS

Ways to Make Modern Ovens Better

Modern humidity-controlled ovens such as CVaps and combi ovens share a common flaw: they don't let you set the wet-bulb and dry-bulb temperatures directly (although the CVap does let you set it indirectly). Why the designers chose to make them that way is difficult to comprehend. These two temperatures are the primary parameters that control cooking, and they are based on concepts that are reasonably easy to grasp. Substituting the arbitrary scales of "Browning" and "Humidity" may seem simpler in theory, but in practice, it means that users need lots of trial and error to find the settings that work best.

So we appeal to the oven makers of the world, especially the many innovative engineers and designers who work in the industry: please give us ovens that let us select separate wet-bulb and dry-bulb temperatures! And while you're at it, clever engineers, perhaps you could solve a related problem: the inadequate precision of the humidity- and temperature-control systems in these ovens. Both temperature and humidity levels stray from the set points more than they should.

This deficiency results largely from their heritage. The CVap started out as a holding oven, and the combi oven was meant to be a catchall appliance for commercial kitchens, a culinary utility fielder. Neither was originally envisioned as a precision tool for high-end cooking. Design engineers have made clear improvements in each of these oven types. But they have not yet captured their full potential.

Accurate and stable control of wet-bulb and dry-bulb temperatures is critical to successful high-end cooking using these techniques. To brown food perfectly without overcooking its interior, for instance, an oven must be able to maintain low wet-bulb temperatures and high dry-bulb temperatures simultaneously. The ideal wet-bulb temperature is 45 °C / 113 °F for cooking fish, 50–55 °C / 122–131 °F for rare to medium-rare meat, and 60–70 °C / 140–158 °F for braised dishes. You want to hold those wet-bulb temperatures steady while maintaining dry-bulb temperatures in the range of 100–300 °C / 212–572 °F. These conditions are physically possible, but they would require upgraded heating- and humidity-control systems in modern ovens.

Rational ovens feature a probe that you insert into the center of the food to track the core temperature. The probe has five separate sensors to give you a more accurate reading; the machine's digital control chooses the lowest. That way, you don't need to hit dead center of the food with the tip of the probe.

For large cuts of meat, overnight roasting is effective even with core temperatures in the range of 50–60 °C / 122–140 °F. The size of the meat compensates for temperature fluctuations, which average out during the long cooking time.

For more on how dehydration works, see Drying, page 428.

outer portions will be overcooked because hotter-than-core cooking always creates a gradient of temperatures in the food. To compensate somewhat, use the oven's temperature probe to measure core temperature. You may need to set the probe for less than the target temperature to compensate for overshoot.

We have had success cooking large pieces of food, such as roasts, in this fashion. Built-in programs such as "overnight roasting" effectively mimic the results of cooking sous vide. But you will probably get more desirable outcomes if you cook thinner cuts of red meat or fish sous vide in a water bath or CVap oven, both of which perform better at low temperatures.

Convection mode is quite handy in a combi oven for dehydration and browning. Dehydrating food by setting the Rational humidity to 0% and the temperature below 30–90 °C / 85–195 °F is a common choice that quickly dries foods without cooking them. Remember that drying is a diffusion process, so you can shorten the drying time by slicing the food as thinly as possible.

To brown or sear food using convection mode, set the Rational humidity to 0% and the temperature to 175–300 °C / 347–572 °F. The higher the temperature, the faster the surface of the food will desiccate and brown.

The combi mode works fine for everyday baking as well. The default setting for combi mode on the Rational oven selects 90% humidity, which is a reasonable choice for many general baking tasks.

Cauliflower steaming in bulk quantities highlights the large capacity a combi oven possesses.

As mentioned earlier, the oven will never actually achieve 90% Rational humidity, but there is little reason to change the setting.

Program Cooking

Busy cooks can easily become enamored of the combi oven's unique ability to do program cooking and to carry out programmed recipes automatically. This convenient feature is made possible by the unit's built-in computer controls and the temperature sensors on a probe that you insert into the food. The combi oven is perhaps the most digitally enabled kitchen equipment available today.

Once the cook enters the sequence of desired cooking steps, the program takes the oven through that sequence—different modes at various temperature and humidity settings for specified time periods. You can create your own custom programs for common cooking tasks, or you can use the factory-installed programs.

The idea is to make it simple for kitchens that are staffed by mostly unskilled workers to consistently produce decent-quality food. Just place food in the oven and press graphical icons on a touch screen; the combi oven does the rest. The programs may, in some cases, prompt you to insert a temperature probe, but that's the most you'll be asked to do, beyond perhaps removing the cooked food.

Cooks can customize their own programs, which can use any or all of the oven's modes. A program can have many steps—hundreds in principle, but we've never seen more than a handful. Each step can include any combination of changes to the temperature, humidity, and mode. The oven monitors the temperature probe to determine when the food is done; it can even prompt the operator to load or unload the oven.

These programs work very well in certain settings. The executive chef of a chain restaurant could, for example, supervise the creation of a program for a new dish, then distribute it to each kitchen. Home cooks can automate simple tasks that they find themselves doing repeatedly, or that they tend to botch regularly. We are quite pleased with several programs that we created (for an example, see page 176).

Program cooking bothers some chefs, who complain that it can never produce the same

results that they could do manually. In some cases, there may be an additional motivation for these complaints: the worry that automation will make their jobs obsolete. But professional chefs have little real cause for concern. Using a combi oven in program mode is definitely a labor saver, but it's unlikely to replace a chef's skills in any meaningful way.

That said, several of the factory-installed programs do an excellent job and may even be useful in preparing high-end food. The overnight roasting program is a case in point: it sears a roast or other large cut of meat (including poultry), then cooks it for many hours via low-temperature steam, and holds it until serving time. The process generally takes four to eight hours, but you can extend it to 24 hours if desired. The result easily matches the quality of long-term cooking sous vide, but with the advantage that many roasts can cook simultaneously in a combi oven.

The built-in roast chicken program also performs quite well. It directs one of the machine's most complex cooking procedures, which takes trussed chickens through multiple steps to produce roasts that have extremely crispy skin and succulent interiors. The engineers at Rational developed the program to allow the combi oven to match the qualities found in rotisserie-cooked chicken for restaurants and take-out sections in grocery stores.

The result tends to be a bit overcooked, in part due to excessive temperatures (perhaps dictated by the manufacturer's concern for food safety), but for a conventional and fast technique, it does a great job. We developed a chicken program that, to our taste, does even better (see How to Roast a Chicken in a Combi Oven, page 178), but it takes several times longer to cook.

Perhaps the most appreciated built-in feature is the self-cleaning program. Combi ovens get very messy, because the high-velocity air tends to splatter juices and drippings all over the inside of the oven. Thankfully, the self-cleaning program handles the dirty work. Just put cleaning compound (which comes in large tablets) into the oven, and start the program. Even the dirtiest oven comes out sparkling-clean afterward.

Other programs are less successful. The combi-fry program cooks frozen french-fried potatoes so that they can almost pass as deep-fried. This program works well enough for service in a school cafeteria and other institutional settings or for vanquishing late-night munchies. But few gourmands would consider these combi fries a real substitute for true deep-fried potatoes.

As smart devices get ever more capable (and presumably less costly), there's no reason that the combi oven won't eventually be able to carry out programmed, or even interactive, cooking tasks that better emulate the skills of a practiced cook. Even so, it will at most merely free up cooks to pursue new ways to create terrific dishes.

Each brand of combi oven has its own set of features. This discussion focuses on the Rational SelfCooking Center, the company's most advanced model.

Comparing Cooking Modes

CVap water-vapor ovens and Rational combi ovens have different strengths and weaknesses.

Mode	CVap	Rational	Operating conditions	Note
low-temperature steam	very good	good	dry-bulb and wet-bulb temperatures are identical and less than 100 °C / 212 °F; relative humidity is 100%	for combi ovens, temperature control is typically poor below 60 °C / 140 °F
steam	n/a	very good	dry-bulb and wet-bulb temperatures are 100 °C / 212 °F; relative humidity is 100%	CVaps generate too small a volume of steam to perform true steaming
combi (humidity-controlled)	good	fair to good	dry-bulb and wet-bulb temperatures diverge; oven directly controls humidity	
convection	fair	very good	same as convection baking in a conventional oven; no moisture is added by the oven	CVaps cannot attain temperatures high enough or humidities low enough to do conventional baking
program	n/a	very good	control of oven temperature and humidity is automated	applies to combi ovens only; CVaps can only store single settings

STRATEGIES FOR COOKING IN CVAP OVENS AND COMBI OVENS

		Combi oven settings			
		Temperature		Humidity	
Method	Cooking mode	(°C)	(°F)	(%)	Note
incubation, fermentation, or proofing	low-temperature steam	30–50	85–120	100	
dehydration	convection	30–90	85–195	0	
low-temperature or sous vide cooking	low-temperature steam	30–60	86–140	100	limited, due to temperature inaccuracy
		60–100	140–212		good temperature accuracy
steaming	steam	100	212	100	
baking	combi mode	60–300	140–450	90	more consistent than convection mode
	convection	60–300	140–450	0	promotes drying and browning more than combi mode
frying or grilling	convection	180–300	355–450	0	
programmed cooking	all modes	full range		full range	built-in cooking programs available; custom programming possible

Frying potatoes with herbs

Baking hamburger buns

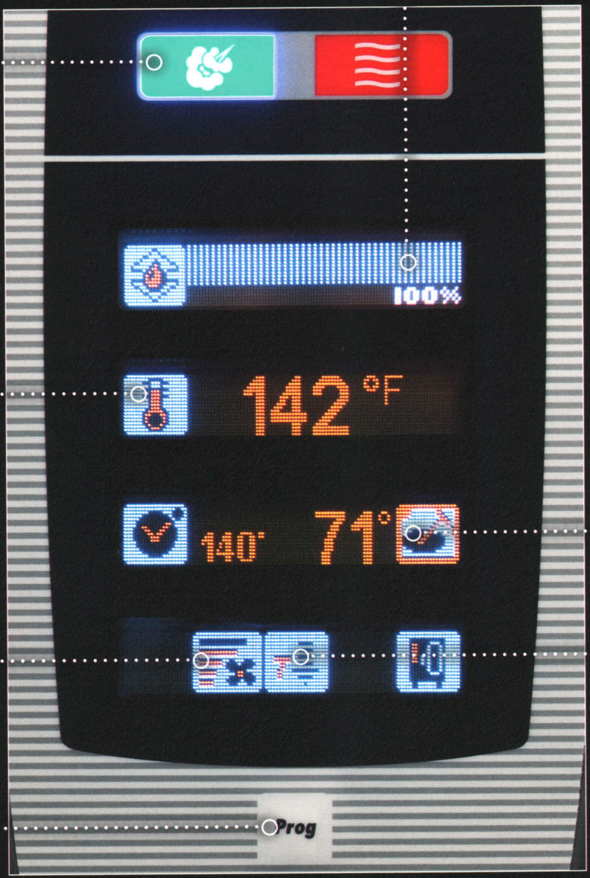
CVap settings				
Doneness				
(°C)	(°F)	Browning	Note	Example use
30–50	85–120	0		yogurt, sausage fermentation
30–60	85–140	1–6	set browning higher for faster drying	fruit leather, vegetable chips, bacon and ham chips
35–93	95–200	0		fish, shellfish, poultry, red meats
not recommended				vegetables, grains, braised meat
60–100	140–210	1–10	low maximum temperature and difficulty achieving low humidity limit its suitability for many baking applications	baguettes, brioches, rustic loaves
not applicable				choux pastries, pizzas, gratin
not applicable			CVaps are not designed to reach the high dry-bulb temperatures necessary for frying and grilling	fried chicken, onion rings, grilled fish and steak, ham
not applicable			no programmability features are available in CVaps, but common settings can be stored as presets	fried rice, rib roasts, omelets


Steaming sausages


Making yogurt

GET WITH THE PROGRAM

Historically, humidity control was the great advantage of combi ovens, but recent advances in digital control systems have also made automation one of their key features. Programmability is convenient for any repetitive task or for executing complicated cooking protocols without error. Advanced combi ovens typically come with a number of programs built in, and you can download additional programs from the Internet. The control panels pictured here are those of a Rational SelfCooking Center; other manufacturers offer digital control systems as well.



The humidity-control touch screen is always set at 100% in steam mode (shown). In dry heat mode (not shown), it can be 0%–100%, but the oven controls humidity by venting only, not by adding moisture. In combi mode (not shown), the oven adds steam to maintain the desired humidity. Note that this setting refers to a proprietary humidity ratio devised by Rational, not the more familiar measure of relative humidity. Depending on the oven's dry-bulb temperature and the relative humidity of the room, much of the range shown on the display may in fact be physically impossible for the oven to attain.

The blue steam button and the red convection button determine the mode in which the oven operates. Press the blue button alone for steam mode, the red button alone for convection mode, or both buttons simultaneously for combi mode.

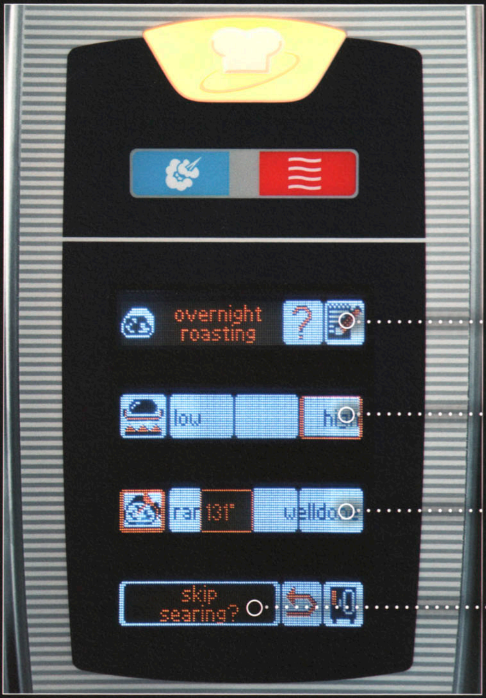
Set the dry-bulb temperature for both steam mode and convection mode using this button. In steam mode, temperatures can range from 30–130 °C / 86–266 °F; convection mode allows temperatures up to 300 °C / 572 °F.

Probe temperature is set and monitored by using this touch screen.

A fan-control button allows you to reduce the convection fan's speed by half.

To vent air from the oven when the door is opened—thus cooling the chamber rapidly—press this button.

Enter new programs using this button.

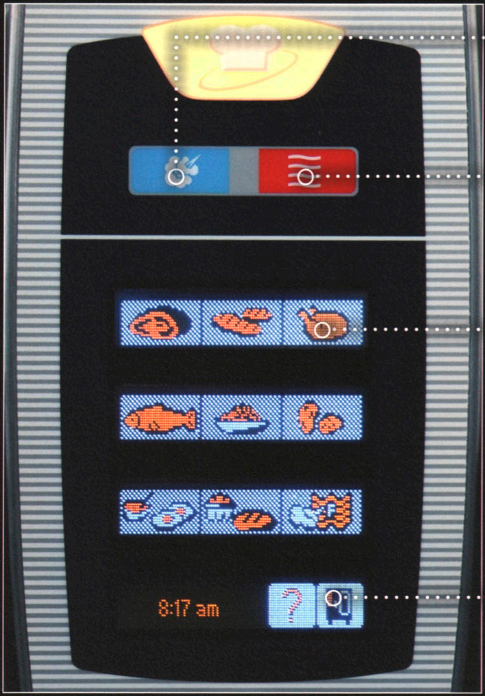


A built-in program quite successfully cooks meat slowly (even overnight) at low temperatures, much as sous vide does. Unlike cooking sous vide, however, you don't need to bag the food, and you can cook much larger volumes: you would need a bank of water baths to equal the electrical power and capacity of even a small combi oven.

The amount of searing is controlled here.

Adjust the target core temperature of the meat by using this control.

Skip the searing step using this option. It's a good idea with small pieces of meat that easily overcook. You can pan sear them instead after cooking.



The steam-mode button, when pressed alone, injects steam at oven temperatures from 30–130 °C / 86–266 °F.

The dry-heat mode button, when pressed alone, replicates cooking in an ordinary convection oven. When pressed together with the steam-mode button, it puts the oven in combi mode. Both modes span temperatures from 30–300 °C / 86–572 °F.

Stored programs automatically cook the various foods depicted by the icons.

Oven maintenance tasks, such as cleaning and set up, are available from this button.

HOW TO Make Bacon and Eggs in a Combi Oven

The combi oven makes perfect ultracrispy, flat bacon and "fried" eggs. The process of "frying" an egg in two stages was pioneered by chefs Pierre and Jean Troisgros and chef Bernard Loiseau, but they used conventional ovens, which made timing correctly or getting consistent results very tricky. Using a combi oven, we can get perfect results every time. Whites and yolks are cooked in separate stages, each at their ideal temperature. Try not to hold the eggs in the oven too long; the controlled temperature can make them rubbery.

BACON

1 **Assemble two sheet trays and two silicone mats for each batch of bacon (not shown).**

2 **Slice the bacon to 1½ mm / ⅝ in thick (not shown).** Partially freezing the bacon before slicing may make this step easier and more precise.

3 **Arrange the sliced bacon on the trays in an even layer.** Place a second silicon mat on top of the bacon and top it with a second baking sheet to hold the slices flat.

4 **Cook in a combi oven at 160 °C / 320 °F and 0% humidity until the bacon is brown and crisp, 20–30 min (not shown).** If you prefer really dry bacon, remove the top tray and silicon mat, reduce the heat to 79 °C / 174 °F, then dehydrate for another 20–30 min.

The exact cooking time depends on the moisture content of the bacon. A sugar-based bacon cure browns quicker and needs a lower temperature.

"FRIED" EGGS

1 **Butter several 10 cm / 4 in baking rings and place them on a very flat baking sheet lined with a silicon mat (not shown).** Alternatively, use the Rational baking tray designed for cooking eggs (see page 166).

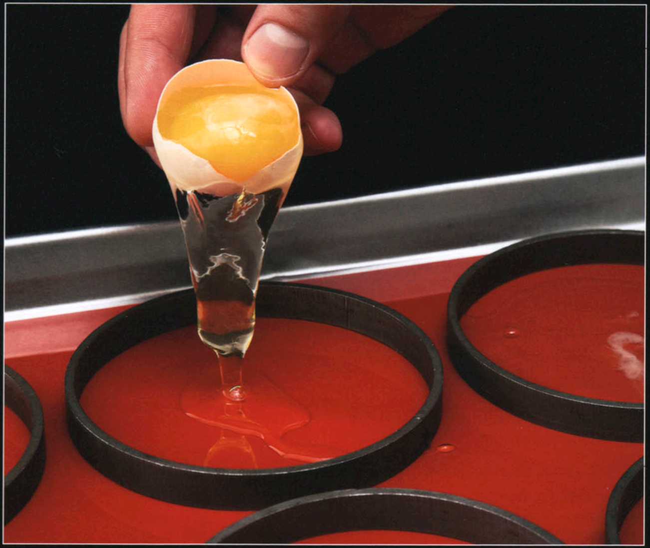
2 **Place one egg white in each buttered ring, reserving yolks.**

3 **Cook the egg whites in a preheated combi oven at 79 °C / 174 °F and 90% humidity for 15 min.**

4 **Reduce the oven temperature to 63 °C / 145 °F.** You may need to leave the door open a bit to cool the oven down. Check oven temperature (via temperature probe or by pressing the temperature-control button) to verify that it is at the proper temperature before going on to the next step.

5 **Place a single egg yolk in the center of each egg white and cook for 25 min.**

6 **Unmold the "fried" eggs and serve.**



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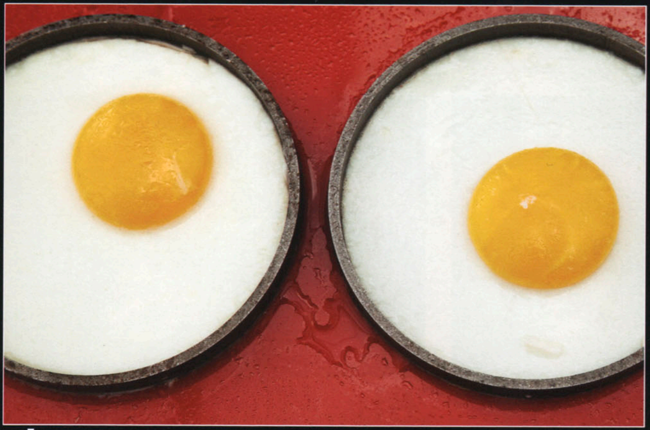
Note that this recipe can be made in a CVap oven just as well. Be sure to vent heat from the oven in step 4, and wait until the temperature stabilizes, about 5–10 min.



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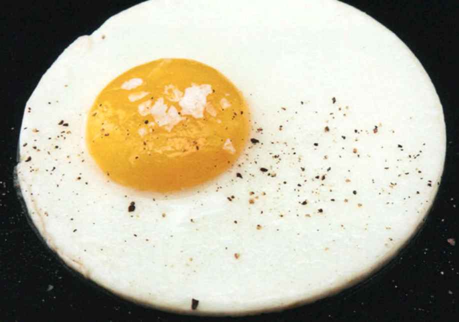

CANTONESE FRIED RICE

Yields 1.2 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Chicken fat, rendered, see page 3·116	56 g	7%	① Preheat oven to **245** °C / **475** °F. ② Add fat to nonstick roasting pan, and let heat. ③ Add mushrooms, followed by sausage, and oven-fry until mushrooms soften and sausages blister, about 5 min.
Shiitake mushroom, thinly sliced	80 g	10%	
Chinese sausage, thinly sliced	80 g	10%	
Jasmine rice, cooked and cooled	800 g	100%	④ Add, stir to evenly distribute other ingredients into rice. ⑤ Oven-fry for 3 min.
Garlic chives, cut into 5 cm / 2 in lengths	80 g	10%	⑥ Add, stir to distribute evenly, and oven-fry for about 30 s.
Scallions, white only, fine julienne	40 g	5%	
Red Thai chili, seeded and cut in fine julienne	2 g	0.25%	
English peas, shucked and blanched (frozen peas work)	80 g	10%	⑦ Fold into rice and oven-fry for about 2 min. ⑧ Remove rice mixture from oven, leaving heat on.
Duck egg, beaten	160 g (four eggs)	20%	⑨ Make a well in the middle of the fried rice. ⑩ Return rice mixture to **245** °C / **475** °F oven to heat. ⑪ Add egg, and allow to cook until just coagulated, about 1½ min. ⑫ Remove fried rice from oven.
White soy sauce	32 g	4%	⑬ Combine liquids and stir into fried rice evenly to season. ⑭ Check seasoning and serve.
Dark soy sauce	24 g	3%	
Mushroom soy sauce	12 g	1.5%	
Toasted sesame oil	1.5 g	0.4%	

(2008)

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3b

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6a

6b

11a

11b

This recipe uses a combi oven as a substitute for a wok to fry the ingredients. A combi oven has a big advantage over a wok if you want to cook in quantity. In the example photos, we made one half-sheet pan of rice, but we could have made five pans' worth simultaneously.

13

A variety of vegetables will work, such as mushrooms or scallions (photo below). It's entirely up to the cook what to include.

HOW TO Roast a Chicken in a Combi Oven

The classic roasted poultry we have grown to love can be amazingly better when you fully exploit all the bells and whistles the combi oven has to offer, including low, precise temperature control, humidity control, and the space to hang the bird while it cooks. Together, these features ensure that the breast and thigh meat are never overcooked and the skin is always golden and crispy brown.

COMBI OVEN ROAST CHICKEN

Yields 650 g

INGREDIENT	QUANTITY	SCALING
Whole chicken	2.0 kg	100%
Water	200 g	10%
Salt	16 g	0.8%
Water	200 g	10%
Salt	10 g	0.5%
Frying oil or clarified unsalted butter	as needed	

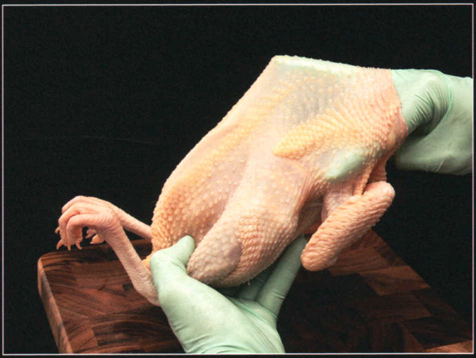
(2010)

PROGRAM

STAGE	TEMPERATURE	HUMIDITY	COMMAND
1			① Preheat oven to **62 °C / 144 °F**
2	**62 °C / 144 °F**	0%	② Roast to a core temperature of **60 °C / 140 °F**, about 3 h.
3			③ Remove chicken, and let rest 45 min.
4	**300 °C / 575 °F**	0%	④ Brush chicken with oil. ⑤ When oven has reached temperature, place chicken in oven, and sear for 7 min.

This recipe meets food safety at the 7D level, according to the Juneja data for both thighs and breast meat (see page 1·181). During the long slow-cooking process, the core temperature of the chicken spends so much time between 55 °C and 60 °C / 130 °F and 140 °F that it reaches the 7D pasteurization level even before the meat core temperature reaches 60 °C / 140 °F.

1 **Make brines (not shown).** Whisk together 200 g of water with 16 g of salt until dissolved to make 8% brine. Repeat with 200 g of water and 10 g of salt to make a 5% brine. Reserve.



2 **Separate the skin from the meat.** Wearing gloves, work your fingers under the skin to detach it from the surface of the meat over the entire body of the chicken. Be very careful not to tear the skin.

3 **Inject the breast meat with an 8% salt brine (not shown).** Fill the syringe with brine equal to 10% of the weight of the bird. For a 1 kg bird, for example, use 100 g of brine.

4 **Hang the chicken by its legs in the refrigerator for 48 h.** The brine will diffuse fully, and the skin will dry out.

As an alternative to air-drying in a refrigerator for three days, put the chicken in a blast chiller for 2–4 h on the chill (not freeze) setting. The air-drying step can also be omitted—the first cooking step may take a bit longer, and the skin will not be quite as crispy, but it will still be much crispier than when roasted conventionally.

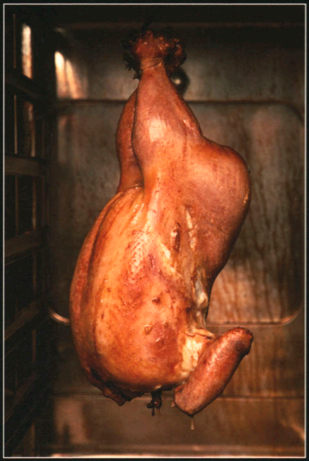
5 **Just before cooking, inject the breast again, this time with the 5% salt brine.** Use an amount of brine equal to 5% of the weight of the bird.

6 **Cook at 64 °C / 147 °F and 0% humidity until the core temperature of the breast meat is 60 °C / 140 °F, about 4 h.** Cook the bird hanging in the oven above a drip tray.

Holding the core temperature of the bird between 55 °C and 60 °C / 130 °F and 140 °F for about 2 h effectively pasteurizes the meat. For more on pasteurization times for poultry, see page 1·181.

7 **Remove from the oven, and hang at room temperature for 45 min (not shown).** Resting will help the meat retain its juices when it is cut (for details, see page 3·84).

8 **Brush chicken evenly with clarified butter or neutral frying oil.**



9 **Cook at 296 °C / 565 °F and 0% humidity until the skin is brown and crisp, about 7 min.**

EXAMPLE RECIPE

COMBI OVEN RIB EYE

Yields 900 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Beef rib eye, bone in	900 g	100%	① Brush rib eye with butter.
Unsalted butter, melted	as needed		② Place meat on perforated rack, and begin program.
Salt	to taste		③ After stage 5, brush with more butter.

(2010)

PROGRAM

STAGE	TEMP	HUMIDITY	COMMAND
1	**55** °C / **131** °F	100%	④ Preheat the oven to **54** °C / **131** °F in steam mode
2	**55** °C / **131** °F	100%	⑤ Steam until core temperature reaches **54** °C / **129** °F, about 1 h.
3	**55** °C / **131** °F	0%	⑥ Dry for 5 min.
4	**58** °C / **136** °F	0%	⑦ Dry for 5 min.
5	**61** °C / **142** °F	0%	⑧ Dry for 15 min.
6			⑨ Remove steak from oven.
7	**300** °C / **575** °F	0%	⑩ Preheat oven until it reaches temperature, about 10 min.
8	**300** °C / **575** °F	0%	⑪ Sear for 2 min. ⑫ Turn and sear another 2 min.

This cooking program uses 25 min of drying to prepare the surface for searing. During the drying steps, the temperature is increased, but the humidity is decreased so that the wet-bulb temperature does not exceed the cooking temperature. The temperature is increased in stages to give the oven time to get rid of the extra humidity. The temperatures at left are for what we judge to be a medium-rare steak. The temperatures can be adjusted for other levels of doneness by using the table below.

STAGE	RARE	MEDIUM RARE	MEDIUM
1	**51** °C / **124** °F with 100% humidity to core of **50** °C / **122** °F	**55** °C / **131** °F with 100% humidity to core of **54** °C / **129** °F	**60** °C / **140** °F with 100% humidity to core of **58** °C / **136** °F
2	**51** °C / **124** °F with 0% humidity for 5 min	**55** °C / **131** °F with 0% humidity for 5 min	**60** °C / **140** °F with 0% humidity for 5 min
3	**53** °C / **127** °F with 0% humidity for 5 min	**58** °C / **136** °F with 0% humidity for 5 min	**63** °C / **145** °F with 0% humidity for 5 min
4	**56** °C / **133** °F with 0% humidity for 15 min	**61** °C / **142** °F with 0% humidity for 15 min	**66** °C / **151** °F with 0% humidity for 15 min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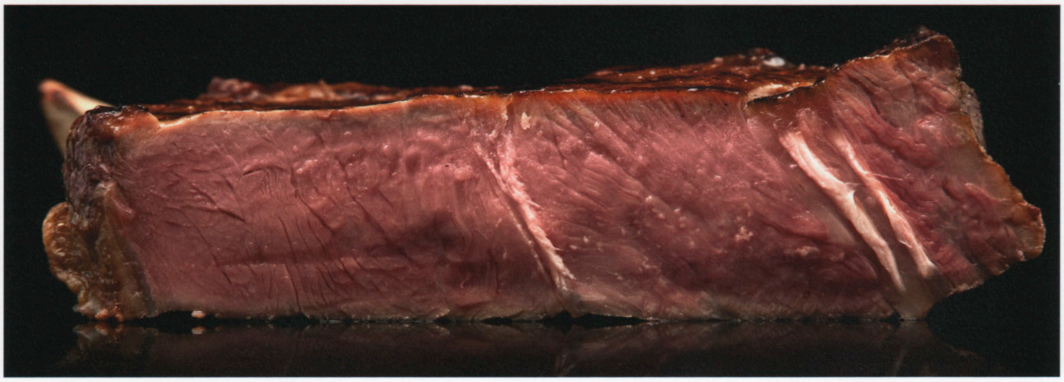


A CVap oven will not get hot enough for the browning stage, but you can do stage 1 in CVap with Doneness at the same temperature as the combi oven examples and with Browning at zero. Sear with a torch, *plancha* or other means (see page 267). The drying stage can be done by then increasing the Texture setting to 4.

EXAMPLE RECIPE

COMBI OVEN–STEAMED BROCCOLI

Yields 1.5 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Rice vinegar	100 g	10%	① Whisk together to make pickling brine.
Sherry vinegar	100 g	10%	② Bring to simmer.
Water	64 g	6.4%	③ Reserve.
Sugar	28 g	2.8%	
Salt	3 g	0.3%	
Broccoli stems, peeled and thinly sliced	40 g	4%	④ Combine. ⑤ Pour warm brine over broccoli-stem mixture to pickle.
Shallots, thinly sliced	28 g	2.8%	⑥ Cool completely.
Currants	18 g	1.8%	⑦ Reserve.
Broccoli florets	1 kg	100%	⑧ Arrange florets in one layer in combi oven steam basket. ⑨ Steam at **90** °C / **195** °F and 100% humidity for 8 min, or until desired texture is achieved.
Broccoli, small florets	200 g	20%	⑩ Toss small florets in oil, and place on baking sheet.
Frying oil	50 g	5%	⑪ Oven fry in combi oven at **270** °C / **520** °F and 0% humidity for 4 min.
			⑫ Drain.
Salt	to taste		⑬ Season steamed and fried broccoli.
Pickling brine, from above	to taste		⑭ Strain reserved pickled mixture, reserving brine. ⑮ Toss steamed and fried broccoli with pickles, brine, pumpkin seeds, and chili oil.
Toasted pumpkin seeds	50 g	5%	
Chili oil see page 330	30 g	3%	
Salted lardo, frozen and very thinly sliced	100 g	10%	⑯ Drape over warm broccoli mix, and serve.

(2010)

COOKING WITH MICROWAVES

Numerous misconceptions surround the microwave oven, despite the fact that nearly every home in the developed world now seems to contain one. The common notion that microwaves cook food from the inside out is incorrect, for example; they penetrate only a centimeter or two (perhaps ½–1 in) beyond the food surface. And although the phrase "nuking" food in the microwave has entered the lexicon, microwave radiation has nothing to do with nuclear radiation.

Microwaves are simply light waves, just like those that comprise visible light. And just like visible light, infrared light, and radio signals, microwaves are a specific class of invisible light waves. In the case of microwaves, their **wavelength**—the distance between neighboring sinusoidal crests that distinguishes light waves—ranges from about one millimeter to one meter (0.04–39 in). They feature much shorter wavelengths and higher **frequencies**—measured in hertz (cycles per second)—than do radio waves. On the other hand, microwaves have longer wavelengths and lower frequencies than the infrared light waves that we recognize as radiant heat. Microwaves themselves carry little power; most hair dryers pull more wattage than microwave ovens do.

Like grills and broilers, microwave ovens deposit energy and thus heat into food by radiative transfer, but the **radiative heating** of a microwave works very differently than these other methods do. The microwaves are tuned to a particular frequency that excites vibrations in water molecules—vibrations that generate heat.

Water molecules can receive this kind of transmission because they are **polar** (see Why Water Is Weird, page 1·298). This means that they have a weak positive charge at one end and a slight negative charge at the other. When polar molecules are subjected to an electric field, they rotate to align themselves with the field lines—an electric version of the way a magnetic compass needle spins to face north and south.

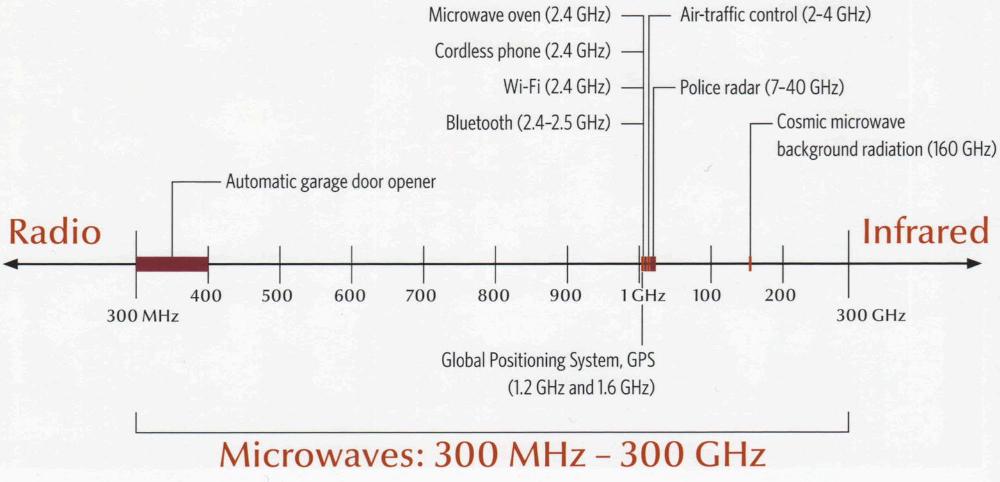
In the rapidly alternating electric field of a microwave oven, the molecules of water and other polar substances spin back and forth repeatedly, transforming electromagnetic radiation into heat. Fats and oils are not polar molecules, but they can also be vibrated in other ways using microwaves, so they also become a source of heat generation. Their vibrations set neighboring molecules in motion, which conducts the heat further afield and eventually heats the entire food by conduction.

Microwave ovens do not heat air, dishes, or the walls of the oven. They heat only water and oil. Dry substances will not heat up at all in a microwave oven. That explains why you can microwave water in a paper cup and still remove the cup with your bare hands: the water heats up; the paper doesn't.

A fatty food was key to the discovery of the cooking potential of microwaves. A Raytheon scientist named Percy Spencer was touring the

For more on radiative heat transfer, see Heat in Motion, page 1·277.

Microwaves don't normally heat dishes or containers. If you put a ceramic dish containing metal in a microwave oven, however, it will heat up—perhaps enough to break. Some special browning dishes are designed to heat safely in a microwave oven.



Microwaves are a form of electromagnetic radiation with frequencies between 300 megahertz (MHz) and 300 gigahertz (GHz). Microwave ovens, cordless phones, and wireless Internet connections all operate at frequencies near 2.4 GHz, which cannot be used for long-distance signals, because water molecules in the atmosphere interfere with their transmission—the same phenomenon that makes these wavelengths perfect for cooking.

Popcorn was one of the first foods cooked in a microwave oven and remains one of the most popular.

company's radar lab in 1945, when he found that a piece of equipment had melted a chocolate bar that he was carrying in his pocket (see page 1·22). The device responsible was a magnetron, a microwave transmitter that served as the heart of the powerful but compact and therefore mobile microwave radar set that British engineers perfected during the Second World War to detect German airplanes and ships. British innovations to the magnetron boosted its power by a factor of 100 over competing designs.

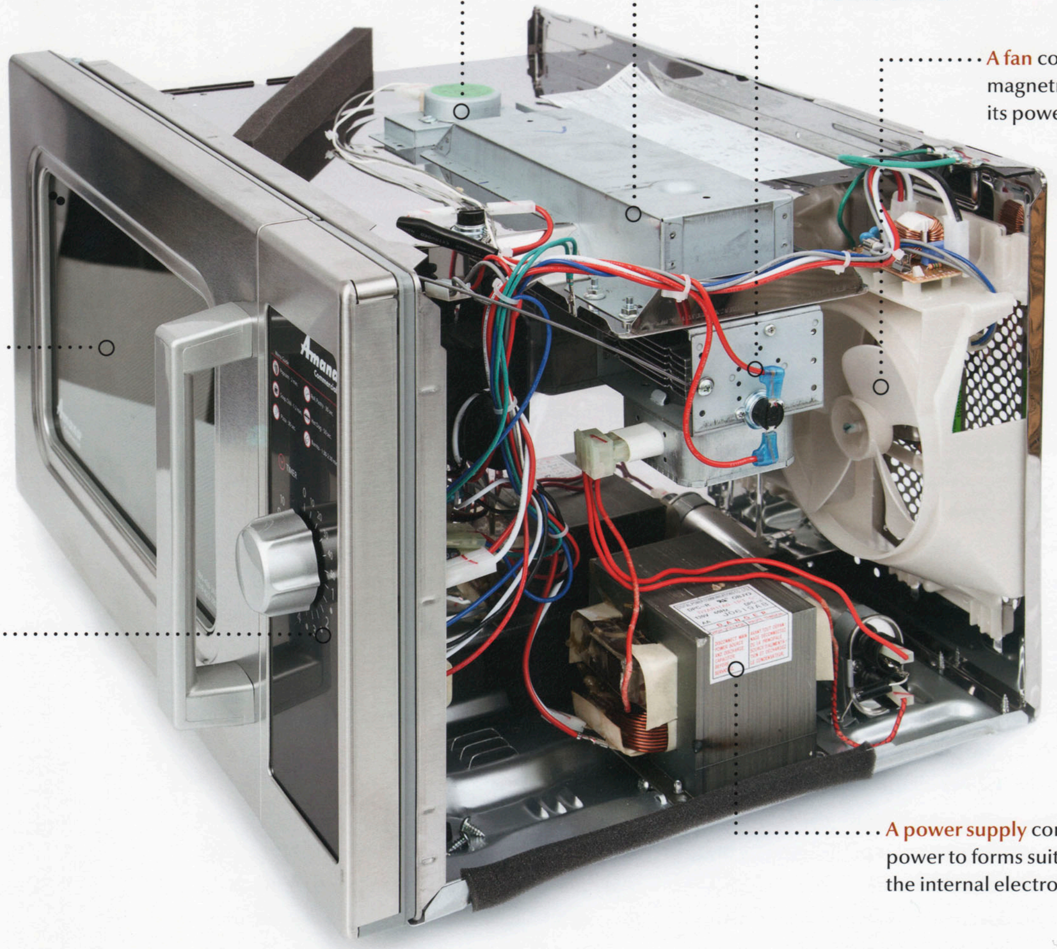
Despite the name, the microwaves that these ovens emit are in fact macroscopic: their wavelength is 122 mm / 4.8 in long, corresponding to a frequency of 2.45 GHz. The reason that it is safe to put screened windows on microwave ovens is that light waves of such a long wavelength cannot escape through the fine holes of the window mesh; they merely reflect back inside.

Microwaves are, in fact, so long from peak to peak that they often "miss" smaller food items that people place in the ovens, and that property has a tremendous impact on the way that they cook food. In a microwave, small things take longer to cook than larger ones—just the opposite of what happens in conventional ovens (see Why Microwaves Heat Small Foods Slowly, page 188). Popcorn pops well in a microwave because all of the kernels are crowded together to form one target mass that "sees" and absorbs the microwaves. Put a whole bag of popcorn in the microwave, and the first kernels pop in less than a minute. An isolated, individual kernel, in contrast, can take minutes to pop. That is why, at the end of the cooking cycle, a few recalcitrant kernels pop with long periods of silence in between—it takes the microwaves longer to heat the smaller, individual kernels.

Despite their macroscopic wavelength, microwaves do not pass through large objects the way that radio waves (whose wavelength is much longer) do. Because microwaves penetrate only a couple of centimeters into food, whole chickens, roasts, and other very thick items do not cook

FROM WARTIME TO SUPPERTIME

The microwave oven is an offshoot of military radar technology developed by British engineers to detect enemy planes and ships during the Second World War. One key advantage of the new device was its size: it was compact and portable. That same feature allowed a new generation of users to tuck a microwave cooking appliance into the slot above a stove. Its sophisticated electronics fit into a small space outside the oven chamber.



This motor runs the fan that distributes microwaves evenly in the oven.

The waveguide carries the microwaves from the magnetron to the food.

The magnetron generates the microwaves.

A fan cools the magnetron and its power supply.

The glass door has a perforated metal shield that allows you to see inside, but prevents microwaves from leaving the oven.

Controls allow the user to set cooking times and power levels.

A power supply converts line power to forms suitable for the internal electronics

STRATEGIES FOR USING A MICROWAVE OVEN

Microwave ovens are often considered to be second-class tools that aren't appropriate for "real" cooking. Yet that ignores the fact that microwave ovens do an excellent job at many kitchen tasks. Microwave ovens are the best tools we know to make beef jerky, for example, or fried herbs for garnishes. Some of our other favorites are listed in the table below. One issue to keep in mind with microwave ovens is that their wattage—and thus the amount of heat delivered to food—differs from model to model, so some experimentation is required to fine-tune recipes and techniques to the oven you are using.

Strategy	Application	Power setting	Example use	See page
cooking	vegetables	high	steamed bok choy, sous vide potatoes	3·313
	seafood, tender meat	low	tilapia steamed with ginger	3·115
defrosting and melting	frozen food, butter, fat	low	melting chocolate	
drying or dehydrating	fruit or vegetable powder	medium	tomato powder	3·311
	meat	medium	beef jerky	3·184
frying	herbs and tender greens	high	fried parsley and carrot tops	3·312
puffing	puffed snacks	high	tapioca puffs, pappadam	4·302
	grain		popcorn, barley	4·307
warming	heat briefly to serving temperature	low to medium	cheese and nuts	

MAKING WAVES

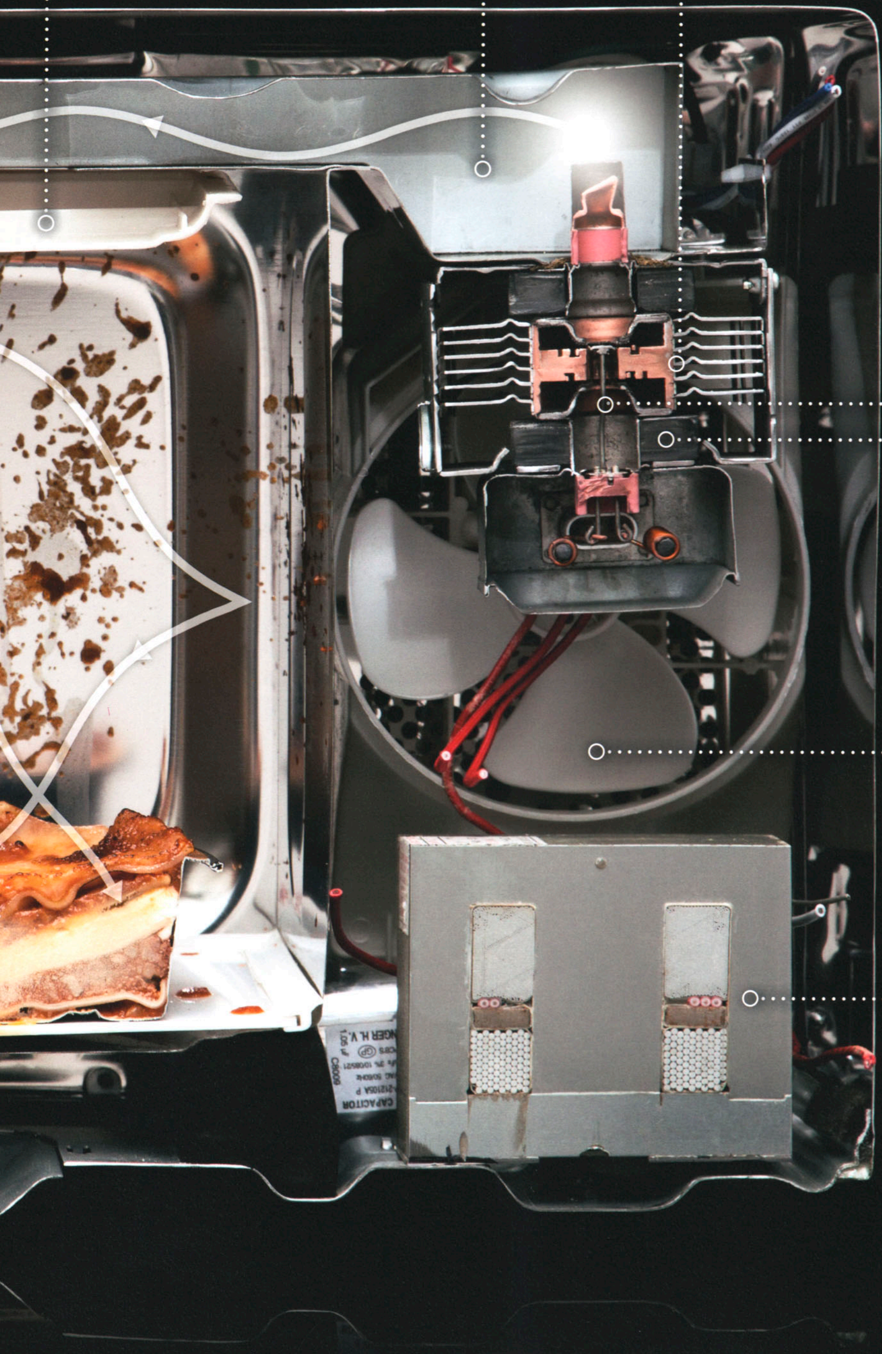
Microwave ovens bathe food in 2.45 GHz microwaves, a form of electromagnetic radiation with frequencies between those of radio waves and infrared light. The magnetron pumps microwaves into the oven chamber through a thin metal duct called a waveguide. When the microwaves hit the food, they heat it by causing water and oil molecules to vibrate. Anything that is dry and oil-free—food, utensils, and containers—experiences no heating.

The fan motor gently rotates the fan blades to mix the microwaves and help prevent hot spots in the oven chamber.

The walls of a microwave have no insulation because neither they nor the air in the oven become hot.

Splatters happen when small steam explosions occur near the food surface. This happens more often in microwave ovens than in conventional ovens because microwaves do not heat food evenly, so some spots get much hotter than others.

Frozen food such as this lasagna becomes piping hot in some places while remaining frozen in others. As cooking progresses, diffusion of heat within the food helps to even out such temperature differences.



The plastic guard over the waveguide opening is transparent to microwaves; they simply pass through it, as they do through plastic containers holding food.

The waveguide is a duct that carries the microwaves from the magnetron to the oven chamber.

The magnetron generates the microwaves used to cook the food.

A filament in the magnetron heats up and emits streams of electrons as high-voltage electricity flows through it.

A magnet inside the magnetron creates an electromagnetic field that causes electrons to swirl around conductive plates, setting up an oscillation at 2.45 GHz that creates the microwaves.

A cooling fan circulates air over the power supply and the cooling fins of the magnetron to make sure the parts do not overheat.

A transformer converts AC-line voltage into the proper voltage for the magnetron.

THE PHYSICS OF

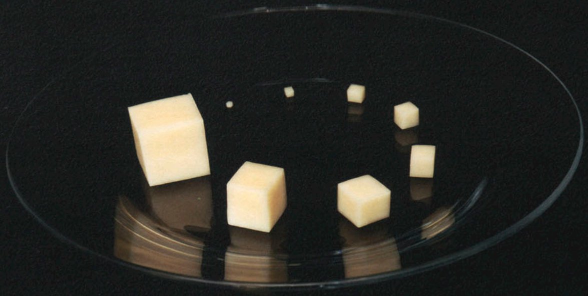
Why Microwaves Heat Small Foods Slowly

Anyone who has cooked food in a microwave knows that these appliances can perform in unexpected ways. Smaller food items can take an inordinately long time to cook, for example. The explanation for this phenomenon revolves around the relationship between a food's size and the rate at which it heats up. In conventional ovens, larger foods take longer to heat up than smaller ones do. In microwave ovens, in contrast, smaller items take longer to warm up than larger ones do.

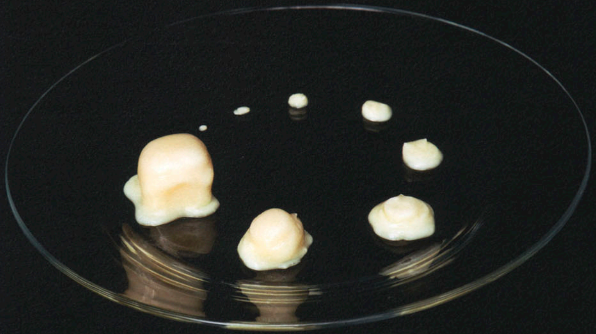
In both cases, the determining factor is the ratio of the food's surface area to its volume. Small food items have higher ratios than large ones. In conventional ovens, surface area is critical, because hot air transfers heat from the surface to the core, so foods with a high ratio of surface area to volume will heat more rapidly.

But microwave heating is more than skin-deep; although microwaves do not cook foods from the inside out, as is sometimes claimed, they do penetrate up to a couple centimeters into the food, so microwave heating depends less on surface area than conventional heating does.

In short, the volume of food counts more for the heating process in microwaves than surface area does, and more is better—up to a limit. To make matters worse, small foods may be too small even to absorb microwaves, which have wavelengths more than 10 cm / 4 in long. They may sit on the turntable for quite a while, unaffected by the radiation beaming all around them.



Cheese cubes heated in a conventional oven melt at a rate that corresponds to their size.



The smallest ones melt fastest, while the largest pieces barely melt at all.

When heated in a microwave oven, the largest cheese cubes melt most quickly, while the small cubes don't melt at all.

quickly in a microwave oven. For the heat to reach the center of the food, it must move by the slow process of thermal conduction, just as if that food were cooking in a conventional oven or on a stove top. A one-gallon / 3.8-liter jug of water, for example, will take about the same time to come to a boil in a microwave as it would on a hot plate or stove top. The best approach to microwave cooking is thus to choose food that is not too small and not too big.

Engineers have fitted microwave ovens with metal fans to "stir" the incoming microwaves by reflecting them every which way, much as a mirror ball distributes a reflected spotlight around a dance floor. Sending the microwaves in all directions helps to distribute their heating effect throughout the food. Without this diversion, the waves would travel as a single beam from the magnetron duct, blazing a hot trail straight through any food in their way, while leaving surrounding food raw. This tendency also explains why many microwave units feature rotating turntables.

Even if you size the food to match the beam pattern, however, microwave ovens can be tricky to operate because they do not have standard power settings. You have to get used to your own machine's idiosyncrasies, and that generally involves determining the most favorable cooking times for various dishes by crude trial and error.

What's more, many cheaper microwave ovens have only the most basic of controls. In these models, the microwaves are either on or off; the only variables you set are the total cooking time and the power level, which is accomplished by cycling the magnetron on and off. Power level is usually measured by a numerical scale that corresponds to the ratio of the time power is on versus the total cooking time. Full power means that the magnetron is on all the time, 50% power means that it is on half the time, and so forth.

Newer, more costly microwave ovens incorporate inverter technology, which directly controls the strength of the microwaves so that the magnetron can stay on throughout the cooking process. Although that feature ought to be an improvement, in practice the results are pretty similar to on–off power control for most cooking situations.

One of the main shortcomings of microwaves is that they will not normally brown food. This is unavoidable; it results from the technology's fundamental cooking process. Microwaves heat food by exciting water molecules in the food to vibrate, but food cannot brown until the applied heat drives off all of the water at the surface. The basic physics indicates that, at just the moment when the last bit of water vaporizes from the food surface and the oven is primed to start browning, microwaves become essentially ineffective, for there is too little water left in the food for them to vibrate and heat the dish!

Another problem for browning is that microwaves penetrate food, whereas browning is a surface phenomenon. In a hot oven—or under a broiler—you create a browned layer less than 1 mm / 1⁄32 in thick. In a microwave, you can't heat just the top millimeter; you must heat a layer 10–20 times that thickness.

You can exploit the limitation on browning in drier foods by using microwave ovens to fully desiccate them without ever burning them: items such as herbs (see page 3·312) and meat jerky (see page 3·184), for example, in which browning is not important or desirable. Microwave ovens also allow you to crisp food with little fear of burning it. Dry foods that are naturally high in fat will brown because fat will not evaporate the way water does, so it keeps on heating the food after the water is gone. In some cases, you can brown food in a microwave by first rubbing oil on its surface.

Engineers have developed various hybrid schemes to compensate for the microwave's browning problem. Some of these hybrid devices are microwaves that incorporate a broiler element for browning. Others, such as the TurboChef brand high-power microwave oven, include a convection oven as well. The TurboChef oven uses microwaves for rapid heat transfer while also using hot air (up to 260 °C / 500 °F) for browning.

Tilapia cooks beautifully in a microwave; see our recipe on page 3·115.

HOW NOT TO Do Irresponsible Things with a Microwave

We certainly do not recommend using kitchen equipment irresponsibly—but the reality is that people have been sticking odd things in microwaves for years, as hundreds of rather amazing YouTube.com videos show. These questionable escapades may damage your microwave and could even be dangerous, so again, for the record, we suggest you not perform these actions, interesting though they may seem!

1 **Plasma grapes:** cut a grape in half down the center, leaving a seam of skin connecting the two halves. Microwave on high. Hovering blobs of plasma emerge from the grape.

2 **Toothpick inferno: stick a toothpick into a piece of cork, light the other end on fire, and put the burning toothpick into the microwave (cork base down) under a clear glass.** Balls of fire will unfurl from the burning toothpick.

3 **Sparks from aluminum foil: crinkled foil and foil edges cause arcing.**

4 **Incandescent light show: fill one glass with water and put a light bulb in another glass.** Put both glasses in the microwave turntable and turn it on for three seconds (use the low-power setting if it has one). Don't leave it for too long and be careful when you remove the glasses: the light bulb gets hot.

5 **Soap monster: microwaves heat the fats in soap, causing rapid and uneven foamy expansion.** Put a bar of soap in a *big* bowl—the soap expands a lot. This trick also works with marshmallows.

6 **Dancing plasma: put a short candle in the microwave, with an inverted glass jar over it, propped up so air can get in.** Light the candle and start the microwave. The microwaves excite the hot gases, turning them into a plasma.

7 **CD light show: a microwaved music CD or CD-ROM (left) generates a spectacular light show as electrical currents short out the thin layer of metal on the otherwise plastic disc.** Don't let the CD cook for more than five seconds or it will start to smoke, releasing hazardous gases.

THE PHYSICS OF

Microwave Myths and Reality

Microwaves are perhaps the most misunderstood appliance in the kitchen. Here we explode several common myths.

Myth: You can't put metal in a microwave.
Fact: Microwaves already have plenty of metal in them: the walls of the oven, the fan, and so on, are all metal! What you need to be careful of is *metal that has sharp points or edges.* Those features concentrate the electrical field in the oven and cause arcing. Arcing in and of itself isn't too dangerous, but it can ignite dry flammables in the oven. The reason not to use metal cookware is that microwaves cannot penetrate metal, so your food will not cook.

Myth: Microwave ovens use nuclear radiation.
Fact: Microwaves are electromagnetic radiation that occurs at frequencies between 300 MHz and 300 GHz. They are made of the same stuff as visible light and have nothing to do with radioactivity or nuclear reactors, despite the fact that the term "nuke" has entered common parlance.

Myth: Microwaves cook from the inside out.
Fact: It may seem that way, because the interior of food heats so much faster in a microwave than in a conventional oven and because you don't typically put very large foods into microwave ovens. But microwaves actually penetrate only a couple centimeters into food; the rest of the food heats by conduction, just as it does in conventional ovens.

Myth: Microwaves are always faster than conventional ovens.
Fact: There's an optimum size of food that microwaves will indeed heat very fast. But very large foods, such as roasts, and very small foods, such as individual kernels of popcorn, will heat much more slowly than they do in conventional ovens, and very dry foods may not heat at all.

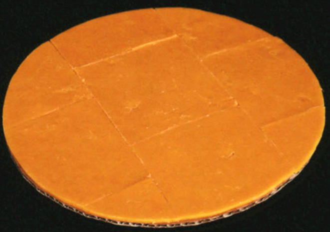
THE PHYSICS OF

Finding the Speed of Light in Your Microwave

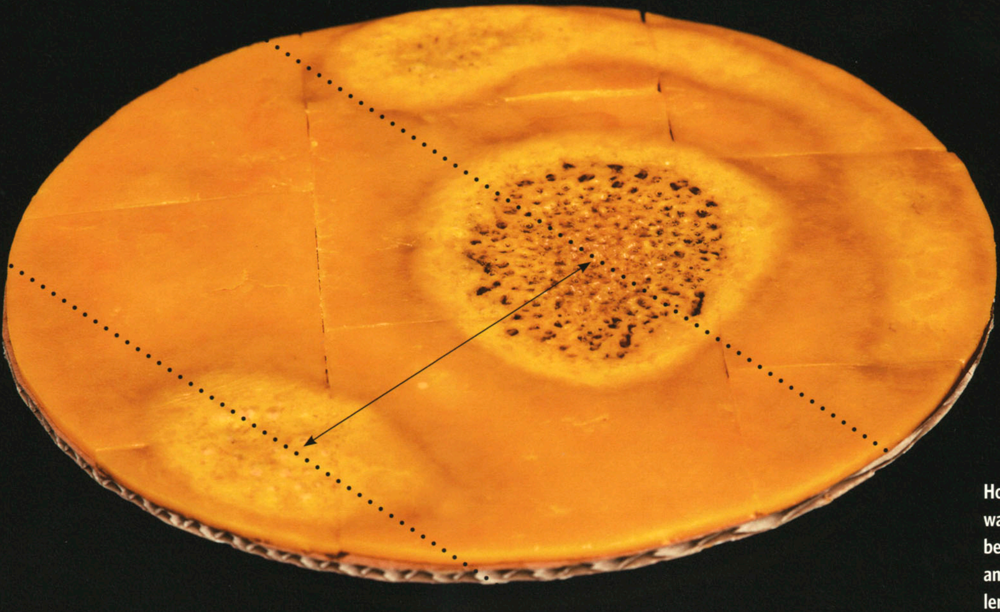
Early scientists thought up many inventive schemes for measuring the speed of light. In the 17th century, Danish physicist Ole Rømer tried to deduce this universal constant by observing, through a telescope, the discrepancies in the orbital period of one of Jupiter's moons. In the 19th century, French physicist Léon Foucault directed a beam of light to a rotating wheel of mirrors for the same reason.

All they really needed, however, was a microwave oven and a slice of Velveeta cheese. You can measure the speed of light by melting cheese, chocolate, or even marshmallows in your microwave. Microwave cooking leaves patterns of melting on soft, smooth surfaces that correspond to roughly half the wavelength of a microwave. These patterns are caused by the way the microwaves crisscross in the oven chamber and either combine their energies or cancel one another out.

Put the cheese or chocolate on a plate and heat it on low power until it has melted in several spots. Measure the distance between the melted areas, then double it to get the wavelength. Next, find your machine's frequency, which is listed on the back of your microwave (it's typically 2.45 GHz). Finally, multiply that frequency by the wavelength to get the speed of light. See how close you can get to the accepted figure: 299,792,458 meter per second (186,282 miles per second). Note that microwave ovens with a turntable will not work for this experiment unless you disable the turntable.



Cheese slices on a cardboard pizza disc



Hot spots form at intervals a half wavelength apart. Measure the distance between the centers of the melted areas and double it to determine the wavelength of the microwaves your oven uses.

9 COOKING SOUS VIDE


154.0
°C
°F
P1
P2
P3
120
80
160
40
200
°C
SAFETY SET
RESET
POWER
PolyScience
temperature controller

Pot-au-feu, once a ubiquitous French dish, is fast becoming a gastronomic curiosity in its traditional form (below) because of the economic realities of the modern restaurant. Sous vide cooking simplifies the preparation of this elaborate dish, allowing each component to be cooked to perfection and individual portions to be reheated easily (previous page).

COOKING SOUS VIDE

On a September evening in 1985, a privileged group of diners sat down to enjoy the cuisine of Joël Robuchon, a legendary French chef whose Jamin restaurant in Paris had earned three Michelin stars and a reputation as one of the best in the world. It was in many respects a typical Thursday dinner scene, with business executives and politicians on expense accounts settling into plush leather chairs before tables set with the very best linens, china, and silver. Michel Cliche, Chef Robuchon's trusted aide of many years, was overseeing the cooking and presentation to ensure that the food met Robuchon's renowned standards.

It did not disappoint, and as the guests ate they were also treated to a remarkable accompaniment to their meal: a view of the French countryside whizzing by in a blur. For this evening they were dining not in Jamin but in the *Nouvelle Premiere* car of an eastbound bullet train streaking from Paris to Strasbourg. Even more amazing, the entire meal had been cooked days before in an experimental kitchen in the depths of the *Gare de l'Est* train station. Mr. Cliche had been able to reheat the food in the cramped galley of the dining car without diminishing its quality.

All this was possible because Robuchon's crew had prepared the food **sous vide**, a novel way of cooking and preserving food that, among its other benefits, allows cooks to store and later reheat their creations without sacrificing any subtleties of flavor or texture. The essence of the technique is to seal ingredients inside a flexible plastic bag before cooking them in a water bath, a combi oven, or some other system that permits precise regulation of heat. *Sous vide,* a French phrase, is often translated as "under vacuum," and indeed often (but not always) removing the air from the bag before cooking produces better results.

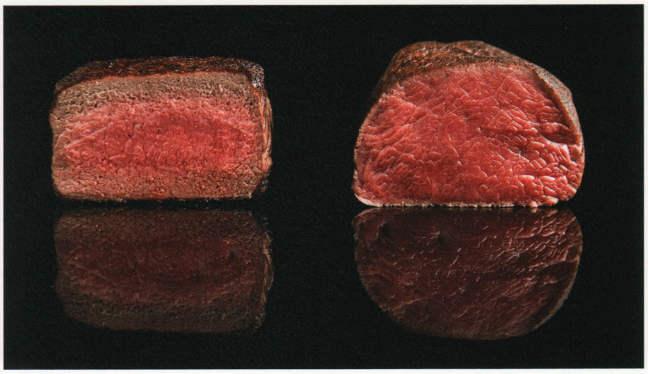
The idea of cooking food in sealed packages is not new. Throughout culinary history, food has been wrapped in leaves, potted in fat, packed in salt, or sealed inside animal bladders before being cooked. People have long known that isolating food from air can arrest the decay of food.

For more on the historical development of sous vide cooking, see From the Vacuum of Space to Vacuums in the Kitchen, page 1·40.

Banana leaves are an ancient form of packaging food for convenience.

Food en papillote (in paper) cooks in a sealed, humid environment.

Both venison tenderloins in the photo above started at the same weight. One steak (at left) was pan-roasted to a final core temperature of 52 °C / 126 °F. The other (at right) was cooked sous vide to the same core temperature, then seared with a blowtorch.

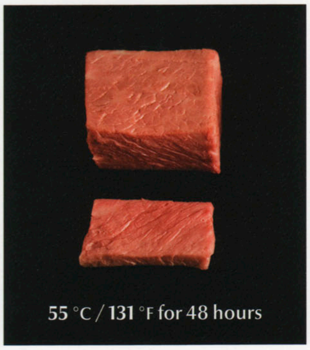


The pan-roasted steak shows more than 40% of the meat was overcooked, becoming gray and dry (above left). The steak cooked sous vide (above right) shows even doneness throughout the meat, as well as an attractive crust.

The defining feature of sous vide cooking thus is not packaging or vacuum sealing but rather the fine control of heat that modern timing and temperature-control technology enable. Sous vide techniques can produce results nearly impossible to achieve by traditional means. A venison tenderloin cooked sous vide at 52 °C / 126 °F has a juiciness and edge-to-edge perfection unmatched by a tenderloin cooked traditionally. The melt-in-your-mouth tenderness of beef short ribs braised at 58 °C / 136 °F for 72 hours is a revelation—and unimaginably difficult to achieve without using a digitally controlled water bath. The delicate, custard-like texture of an egg poached at 65 °C / 149 °F is similarly eye-opening.

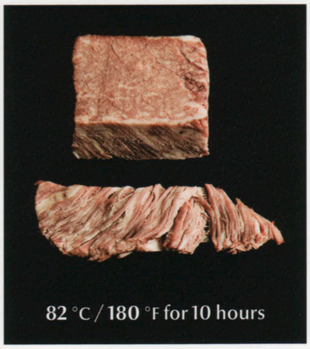
This chapter begins with an explanation of the rationale for sous vide cooking and the options it provides. We then discuss the special equipment used and present various strategies and techniques for sous vide cooking.

Braised Short Ribs (see page 5·42)
58 °C / 136 °F for 72 hours



55 °C / 131 °F for 48 hours

64 °C / 147 °F for 24 hours



82 °C / 180 °F for 10 hours

When cooking temperature can be precisely controlled, braised beef short ribs will yield textures ranging from steak-like to flaky.

WHY SOUS VIDE?

Modernist chefs have embraced sous vide principally because of the unparalleled control it provides over the flavor and texture of the cooked food. Using sous vide, you can heat the food to precisely the temperature you want for precisely the amount of time you desire. Equally important, the heating can be made to happen uniformly, so every region within the food reaches the same temperature. With sous vide, there is no need to overcook or undercook part of the food to achieve a desired level of overall doneness at the center.

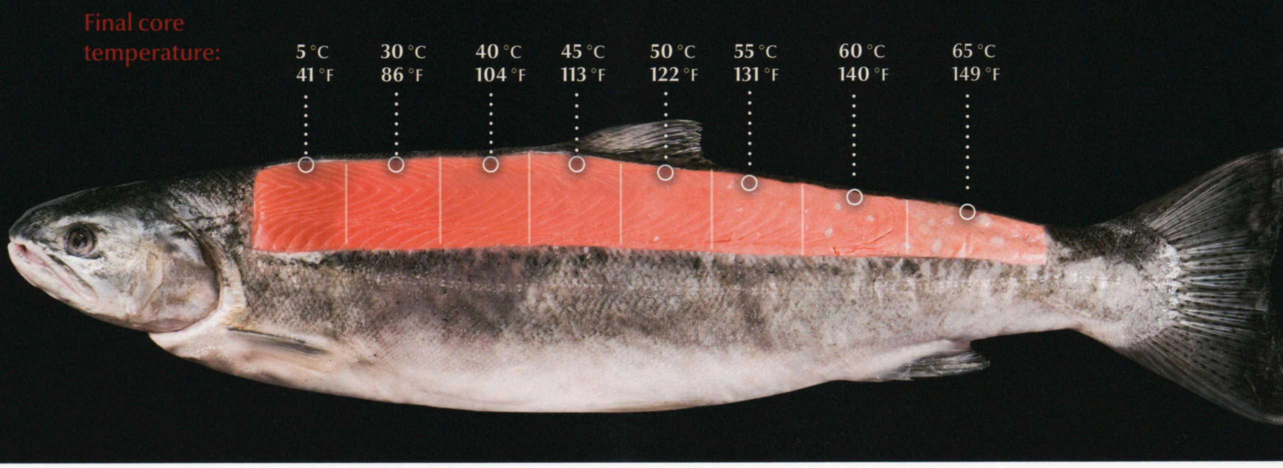
Sous vide is especially useful for cooking meats and seafood, for which the window of proper doneness is often vanishingly small when traditional methods are used. When you fry a piece of fish, for example, the flesh is most succulent and tender within a very narrow temperature range. Although opinions vary about what temperature is ideal, everyone can agree that it is much cooler than the searing surface of the frying pan. Because the cooking temperature is at least 200 °C / 360 °F hotter than the ideal core temperature of the food, the edges of the fish will inevitably be far more cooked than the center is when pan-fried.

Sometimes this steep gradient in doneness is exactly what you want: panfrying can provide a crispy skin and the pleasant grilled flavors of the **Maillard reaction**, for example. But sometimes variations in temperature are just an unavoidable consequence of the cooking method. In either case, the result of the gradient is that the cooking must be timed perfectly. With just a moment's inattention, the core temperature of your fish quickly overshoots perfection.

Perfect timing is complicated further by the fact that food heated by traditional methods continues to cook even after it is removed from the heat. Fish pulled from a frying pan has a hot exterior, which cools down primarily by leaking heat into the core of the food until the entire piece of fish equilibrates to roughly the same temperature. A chef thus must remove the fish from the pan well before the center is done if it is to be perfectly cooked at the time of service.

Sous vide, in contrast, makes it very easy to control temperature accurately. The simplest technique is to place sealed parcels of food in a water bath or a convection steam oven that is set to maintain the desired core temperature. Then you just wait for the food to reach the set temperature, take it out, and serve it. With a computer-controlled heater, a water bath with a high-quality stirring system fluctuates less than half a degree above or below the temperature setting, eliminating undercooking or overcooking. Moreover, when the food emerges from the bath, its surface

Traditional methods of cooking fish require perfect timing that is challenging even for experienced cooks, as illustrated by this composite of salmon cooked in a 180 °C / 400 °F oven for slightly different times.



Cooking sous vide is simple because it eliminates guesswork. In a water bath, you can cook every piece of fish to precisely the same degree of doneness.

and core are already at equilibrium, so it doesn't continue to cook.

Perfect control yields perfect consistency. Because little temperature fluctuation occurs during sous vide cooking, its results are highly repeatable. No amount of skill and judgment can achieve such repeatability when food is cooked over open flames and other less-predictable heat sources.

Sous vide techniques also improve control over portion size, product quality, and food hygiene—all important issues in a busy kitchen. Portions can be quickly weighed, labeled, and seasoned while they are being bagged. When individual portions of salmon are being prepared, for example, olive oil, herbs, and spices can be added to the bag before it is sealed. The entire ensemble is then refrigerated until needed. Weighing each ingredient ensures accurate portion control as well as consistent quality after cooking.

Storing food sealed in plastic bags strikes some as unnatural. That may be true, but vacuum sealing

When combined with proper hygiene and a reliable scale, sous vide cooking can simplify portion control and extend the time that ingredients can be held at the peak of quality. Vacuum sealing individual portions also provides an easy way to add measured amounts of seasoning to each portion, which ensures that every serving is seasoned correctly and consistently.

Thin plastic wraps permit oxygen to seep through. Oxygen binds to myoglobin molecules, initially giving meat its pleasant, fresh, red color (above left). Over time, however, the oxidation changes myoglobin into the brown-colored pigment metmyoglobin. This is why plastic-wrapped steaks soon take on a less-desirable mottled-brown hue (above right).

Sous vide plastic bags preserve the color of steaks because they are mostly impermeable to oxygen. When vacuum sealed, red meat often turns dark (above left) for the same reason that our blood becomes blue when it lacks oxygen. Just like blood, vacuum-packed meat regains its brightness as soon as the air hits it (above right).

Damage to many fruits and vegetables, such as artichokes, results in unsightly browning from melanin pigments. Plants create these pigments to prevent infection of the damaged tissue. Sous vide packaging retards the browning reaction by eliminating oxygen. A raw artichoke heart packaged for sous vide (left half, above) better retains its original color than one exposed to air does (right half).

greatly reduces one of the most vexing problems that nature poses for cuisine: the chemical damage that oxygen causes when it reacts with food. It takes very little time, for example, for the natural fats in fish to oxidize and produce unpleasant fishy aromas. Oxidation is likewise what makes the myoglobin pigment in red meat change from an initially attractive red to an unappetizing brown color (see photos on previous page).

When apples, artichokes, endives, and many other fruits and vegetables begin to brown at their cut surfaces, that process reflects oxygen at work with enzymes called polyphenol oxidases. Sealing these foods in plastic bags that are impermeable to air slows these reactions tremendously, keeping fish smelling fresh, meat from discoloring, and produce from turning brown for far longer than refrigeration alone can.

Inside the vacuum-sealed bag, food also enjoys a fully humid environment. This humidity eliminates drying. As a result, food cooked sous vide is often noticeably juicier and more tender than the same food cooked outside a bag.

The bags protect the food from more than just the atmosphere. Food inside sous vide packets is less likely to become cross-contaminated during handling and storage in the often crowded refrigerators of professional kitchens. When done properly, sous vide cooking may be the best way to ensure food safety.

As with any approach to cooking, however, the proper handling of raw and cooked foods is paramount. The general practices for kitchen hygiene apply as much to sous vide cooking as to any other method and should be given special attention when cooked food is cut into portions and bagged for later reheating.

For more on safe food handling and kitchen hygiene, see chapter 3 on Food Safety, page 1·162.

Control, consistency, quality, safety: these are the benefits of cooking sous vide. Some chefs have criticized sous vide techniques for removing the art and craft from cooking. That criticism misses the point. A busy kitchen offers no shortage of challenges to cooking consistently great food. By guaranteeing perfect consistency in heating, sous vide methods allow cooks to finesse the many other details of great cooking. Furthermore, there is no "right" temperature for cooking most foods. One person may prefer beef short ribs cooked to a steak-like 55 °C / 131 °F, whereas another may prefer the flakier texture that appears around 82 °C / 180 °F. The most important goal is consistently delivering a chef's vision or a guest's preference. Sous vide cooking makes that easier.

For more on egg texture at various temperatures, see page 4·76. For more on meat doneness and texture at various times and temperatures, see page 3·109.

Like artichokes, apple slices turn brown with exposure to air. The discoloration can be slowed by adding lemon juice (left), which works in two ways. Citric acid in the juice lowers the pH, which reduces the activity of the phenolase enzyme responsible for the browning reaction. At the same time, ascorbic acid mops up oxygen, another element in that reaction. Unfortunately, the lemon juice changes the flavor of the apple slices. Vacuum packing the apple slices (right) eliminates oxygen and thus prevents browning without altering the apple's flavor.

Sous Vide Steps

(steps in gray are optional)

1 Prepare ingredients

Trim and portion

Marinate, brine, or cure

Presear

Preblanch

Season

2 Package the food

Place in cooking container

Vacuum pack

Insert temperature probe

3 Set the cooking temperature

Select target core temperature

Select sous vide strategy and set bath temperature

4 Cook for appropriate time

Determine cooking time from recipe, table, or calculation

Monitor temperature probe readout

5 Finish, store, or serve

Rest or cool

Reheat

Sear

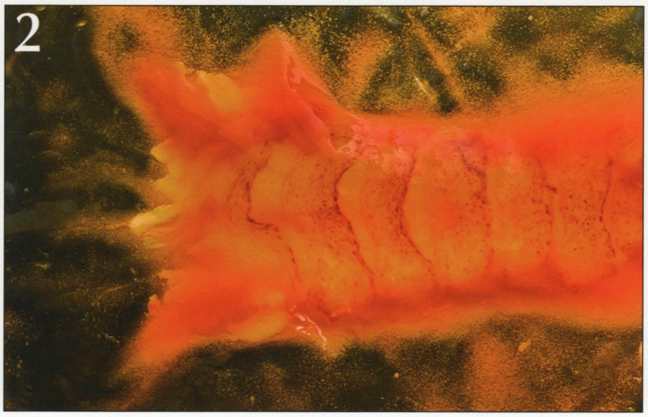
Portion

Store

Serve

1

2



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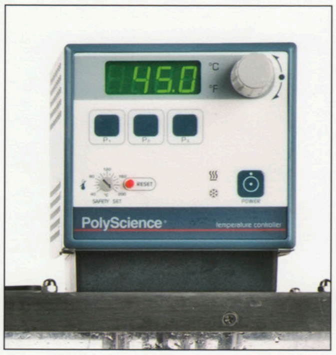

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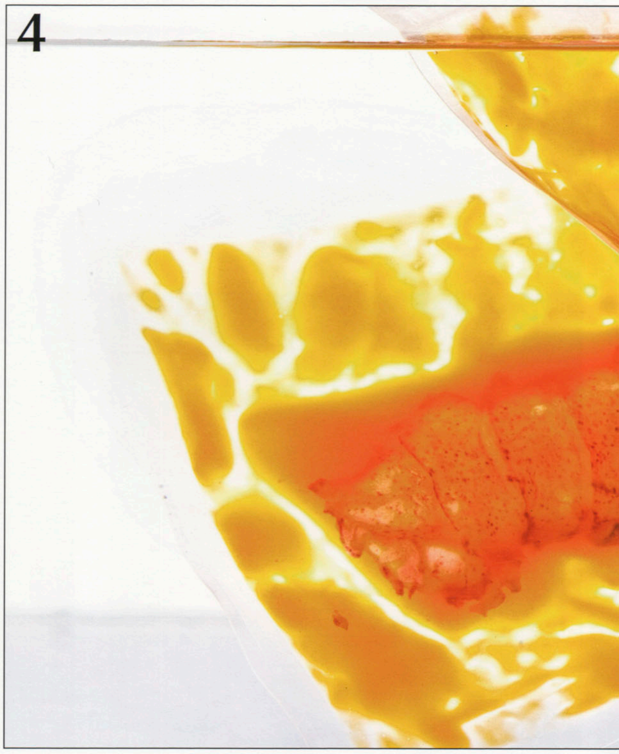


The Sous Vide Cooking Process

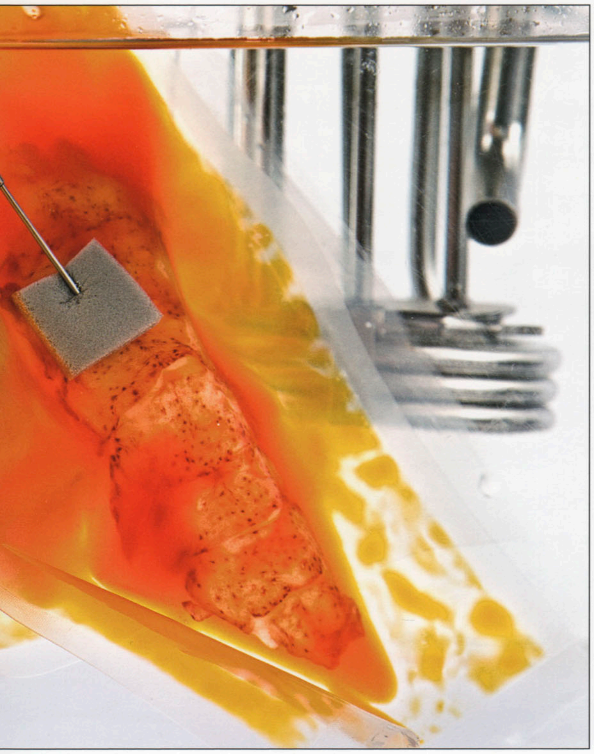
Cooking any food sous vide involves five steps: preparation, packing, temperature setting, timing, and finishing. Preparation of the ingredients and organization of your *mise en place* for sous vide is similar to that for any other cooking technique. When sealing food into packages, restaurants that use sous vide regularly typically rely on expensive chamber-style vacuum packers, but improvised options can cost less. The goal of this second step is to create a sealed, ready-to-cook food package that excludes as much air as is practical.

The most crucial steps are selecting a temperature for the water bath, combi oven, or other cooking equipment, then choosing the cooking time. Should cooking stop as soon as the final temperature is attained, or should the food be held at that temperature for some time? Although the choice is informed by food safety considerations, which we discuss later, the palate of a talented chef is essential. Some choices are more reasonable than others, but there are no hard-and-fast rules about which temperature and time combinations yield the best results. Understanding all of the options available makes it easier to select the best approach for your purpose.

Three broad strategies can be used to cook sous vide: cooking for immediate service, cooking then refrigerating or freezing until needed, and cooking at high enough temperatures long enough to pasteurize food (see Sous Vide Cooking Strategies, next page, for more details).

The final step in the sous vide cooking process is finishing. The cook-chill approach may include further work, such as breaking down a large joint of meat and repackaging the individual portions. When cooking sous vide for immediate service, many items need no work beyond opening the bag and plating the dish. Some foods, however—such as a medium-rare steak—just aren't appetizing without a seared crust.

Later in this chapter, we describe several good strategies for creating the perfectly seared crust while retaining the unique, edge-to-edge even doneness of sous vide cooking.

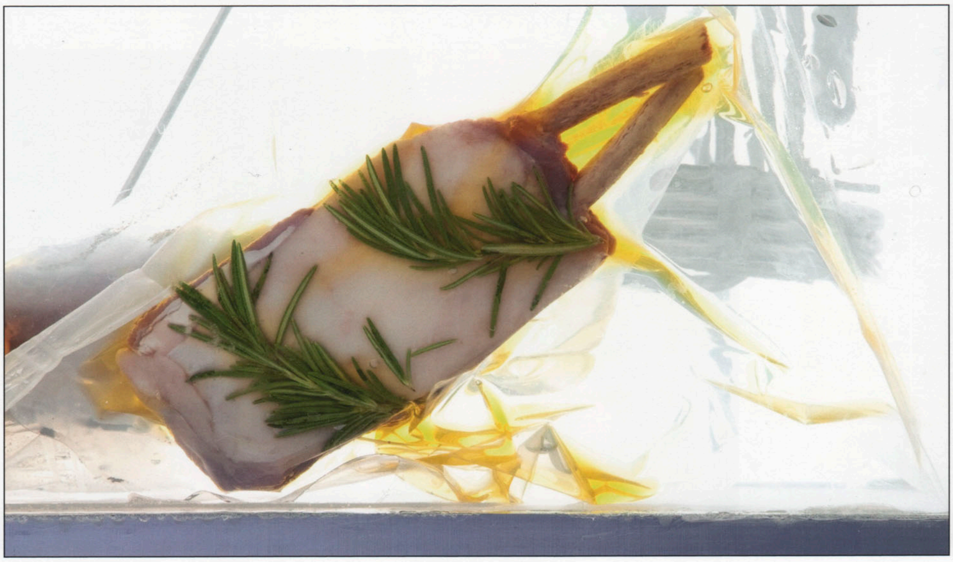


5

SOUS VIDE COOKING STRATEGIES

	How soon will the food be served?	How should the food be stored after cooking?
Immediate service When food will be served and eaten immediately after cooking, chefs have the greatest flexibility in choosing sous vide cooking times and temperatures. This strategy is often the best approach for delicate foods, including fish, crustaceans, and tender meat, which would be ruined if cooked to the extent required for cook-chill or sous vide canning.	within minutes	should not be stored
Cook-chill Cook-chill methods were developed for use in large-scale catering, where meals must be precooked, stored in chilled or frozen form, and later reheated and served. This approach is also convenient for some kinds of gastronomic cooking because it allows advance preparation of complicated dishes and the use of foods that require very long cooking times.	within one week within six months	refrigerator (1–5 °C / 34–41 °F) freezer (below 0 °C / 32 °F)
Sous vide canning Canning is desirable when you need food to keep for long periods of time without refrigeration. Special equipment is needed to do canning with sous vide, including a pressure cooker or autoclave. Both standard canning jars and and retort bags will withstand the high temperatures needed to sterilize the food within. Safety requires strict attention to minimum cooking times when canning—see Canning, page 75.	within six months	room temperature

Immediate service



Cook-chill

How will the food be contained while cooking?	What cooking equipment will be used?	What cooking and storage strategies will be used?	If immersing the food what bath temperatures will be used?
chamber-sealed bag edge-sealed bag impulse-sealed bag zip-closure bag roasting bag open bag retort bag jar or rigid container	water bath combi oven low-temperature steamer steamer pressure cooker autoclave improvised equipment pot on stove	remove at temperature hold at temperature pasteurize for chilling high temperature and pressure infuse or extract age	any, as long as the food spends no more than four hours within the range of 5–54 °C / 41–129 °F For more on this, see chapter 3 on Food Safety, page 1·162.
chamber-sealed bag edge-sealed bag retort bag jar or rigid container	water bath combi oven low-temperature steamer steamer pressure cooker autoclave improvised equipment	extended hold at temperature pasteurize for chilling high temperature and pressure cool freeze thaw or cook from frozen reheat	at least 54 °C / 129 °F for no less than the time required to pasteurize (see chapter 3).
retort bag jar or rigid container	pressure cooker autoclave	sterilize for canning	at least 115 °C / 239 °F

Sous vide canning

THE SCIENCE OF

Common Myths about Sous Vide Cooking

Myth: Cooking food without air increases the risk of foodborne illness.
Why do people think this? The toxin that causes botulism, as well as microbes that produce other serious forms of food poisoning, can develop or grow in vacuum-packed food stored improperly or cooked at too low a temperature.
Fact: All of the evidence indicates that food is actually much safer when stored and cooked sous vide than when cooked in traditional ways. Because the food is sealed before being cooked sous vide, it is less likely to be accidentally contaminated during handling, which is the most common cause of foodborne illness.

Sous vide methods also allow chefs to accurately control cooking temperatures, so they need not guess when the food is done. This improves the margin of safety. As long as cooks adhere to proper guidelines for chilled storage and use acceptable combinations of cooking time and temperature, sous vide methods pose almost no risk of botulism or other serious forms of food poisoning.

Myth: Safe cooking of vacuum-sealed food requires blanching the package in a water bath, typically at a temperature greater than 80 °C / 176 °F, before finishing the cooking at a lower temperature.
Why do people think this? Certain thermophilic pathogens can survive at temperatures that are almost high enough to blanch food.
Fact: Briefly blanching food provides an additional margin of food safety because it pasteurizes the surface of the food. In some cases, blanching is worthwhile (see How to Cook in Multiple Baths, page 248, and Blanching and Searing for Sous Vide, page 267), but preblanching is not required to ensure food safety.

Restaurants that use sous vide cooking methods almost always cook the food quickly to its desired final temperature, then serve it immediately. This practice is safe and permissible if the cooking times are relatively short.

For food that may have surface contamination, cooks often intuitively take an alternative approach that rapidly destroys any pathogens on the surface: they simply sear the food. Whether searing occurs before or after sous vide cooking doesn't matter much; either approach makes the food safer—and often tastier, too!

Myth: Seafood cannot be safely cooked sous vide.
Why do people think this? Most people prefer fish cooked lightly, at time-temperature combinations that are insufficient to pasteurize the food.
Fact: As many restaurant menus note, consuming raw or unpasteurized foods poses some risk, which remains regardless of how the food is cooked. Sous vide cooking neither increases nor decreases this risk. Nor is there anything special about fish in this regard—fish just happens to be commonly served raw or very lightly cooked.

Note that even the times and temperatures recommended by the U.S. Food and Drug Administration for cooking fish (see page 1·184) do not necessarily ensure pasteurization! For more details, see chapter 3 on Food Safety, page 1·162.

Myth: The temperature at which food is cooked sous vide affects how long it can safely be stored under refrigeration.
Why do people think this? Interconnections between pasteurization standards and concerns about the growth of anaerobic pathogens have caused confusion on this point.
Fact: Proper pasteurization is important before refrigerated storage of many foods, regardless of how they are

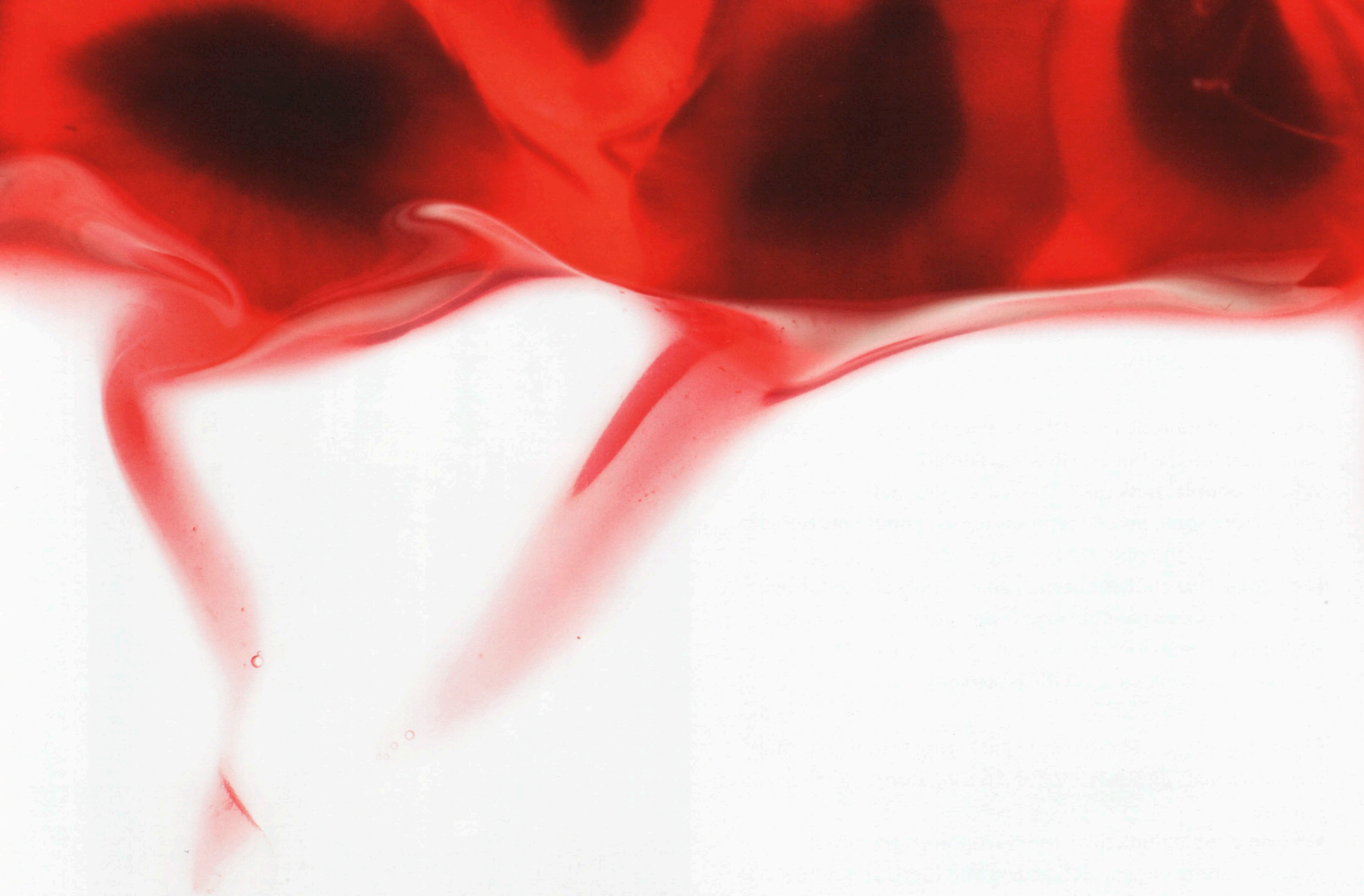
prepared. For guidance on pasteurization methods, see chapter 3. Once pasteurized, foods cooked sous vide may be safely stored for up to three days below 5 °C / 41 °F, for up to 30 days below 1 °C / 34 °F, and for an unlimited period below −20 °C / −4 °F (see page 252).

Myth: Meat must be cooked sous vide to higher temperatures when on the bone than when filleted.
Why do people think this? The reason this myth endures is unclear, but some misconceptions persist about how bones affect the movement of heat within food.
Fact: Meat that contains bones can be safely cooked sous vide. Some bones conduct heat faster and others conduct it slower than meat does, but with the right time and temperature, you can cook meat on the bone sous vide.

Myth: Plastics used in sous vide packaging contain harmful chemicals that can leach into food during storage and cooking.
Why do people think this? Media reports have raised concerns about chemicals leaching into foods and drinks from their plastic containers.
Fact: According to the latest research, the safest plastics for use with food are high-density polyethylene, low-density polyethylene, and polypropylene. Virtually all sous vide bags are made from these plastics, as are most brand-name food storage bags and plastic wraps such as Saran Wrap. Concerns about the safety of sous vide bags are misplaced.

Less expensive, bulk plastic wraps sold to the catering trade are not as safe, however. These products are still commonly made from polyvinyl chloride or polyvinylidene chloride, which can contain harmful plasticizers that have been shown to leach into fatty foods such as cheese, meat, or fish. Legitimate concerns exist about food exposed to these plastics at higher temperatures. Polyethylene-based plastic wraps are available at only slightly higher cost and do not raise such concerns.

Many professional kitchens use clear, rigid, plastic storage containers that are made from polycarbonate. These plastics also may be a cause for concern because they contain bisphenol A (BPA), a chemical that can disrupt hormone activity and can leach into food or beverages. Cracks and crazing due to wear and tear increase the rate at which BPA leaches out of polycarbonates. Polycarbonate containers are currently approved for food use. If you are concerned about BPA contamination, however, replace any polycarbonate containers that have cracks or crazing.



PACKAGING FOOD FOR SOUS VIDE

Vacuum packing is a convenient way to package food for sous vide cooking, but it is not necessary, strictly speaking. One can cook in a sous vide style without vacuum sealers.

For more on aerobic and anaerobic bacteria, see chapter 2 on Microbiology in the Kitchen, page 1·102.

Sous vide has become synonymous with vacuum packing—indeed, the phrase is usually interpreted as "under vacuum"—but that literal translation can be misleading in two ways. Food can be prepared sous vide without vacuum packing as long as the meal will be served within a few hours of cooking. Moreover, the food itself does not experience a vacuum—that is, very low pressure—after it is sealed inside a bag. The weight of the atmosphere still presses down with full force on both the bag and its contents (see How Vacuum Packing Works, page 212). A more apt translation of *sous vide* would be "packed without air," because this accurately describes how we usually prepare food for cooking sous vide.

Vacuum packing is most commonly used to prevent spoilage of food during distribution rather than for cooking. Supermarket shelves are full of vacuum-packed meat, cheese, coffee, and ready-to-eat food products. This technology substantially increases shelf life because it removes oxygen from contact with food. Oxygen is a highly reactive element; that is why iron rusts, fire burns, and some fruits and vegetables (including artichokes, apples, avocados, and endives) brown when their flesh is exposed to air. Oxygen is also essential to the growth of spoilage bacteria, almost all of which are aerobic. By sucking all the air away from the food, vacuum packing simultaneously forestalls the two biggest causes of food degradation with age: direct oxidation and aerobic microbial growth.

Strictly speaking, vacuum packing is only required (as a safety measure and to prevent oxidation) for cook-chill sous vide, in which the food is stored after cooking. Cooks often choose

Pomegranate seeds yield juice without mess when crushed in a sous vide bag—just one of many convenient uses for vacuum packing.

to use vacuum packing even if they are serving the food immediately, however, because it offers numerous practical advantages. Unsealed bags tend to float in the water baths that are often used for sous vide cooking, for example, and holding the bags down with weights or nets is inconvenient. In contrast, vacuum-packed bags generally do a better job of sinking on their own. Removing the air by vacuum packing food offers another advantage as well: it helps prevent chemical reactions that can give cook-chilled foods a warmed-over flavor.

These benefits are admittedly modest, and certainly food can be cooked sous vide without using vacuum packing at all. Even sealing food tightly in an ordinary press-and-seal bag achieves the main advantage of cooking without air, which is consistent temperature control. Because air is a poor conductor of heat, excluding air improves the uniformity of heating. Even more important, water cannot evaporate from the food without air to evaporate into. Without the cooling effect of evaporation, the cooking temperature is always the same as the air or the bath temperature outside the bag.

But if you are going to seal the food anyway, you may as well do it with a vacuum machine. The only important disadvantages of this approach are the cost of the equipment, which can be considerable for a chamber sealer, and heightened (but largely unjustified) concerns about anaerobic pathogens—microbes that thrive in the absence of air. Vacuum-packed food actually poses no greater risk of foodborne disease than food prepared in air. Vacuum packing has drawn attention from regulators simply because it is unfamiliar to them.

For more on food safety issues and precautions in sous vide cooking, see Pasteurizing for Storage, page 249, and chapter 3 on Food Safety, page 1·162.

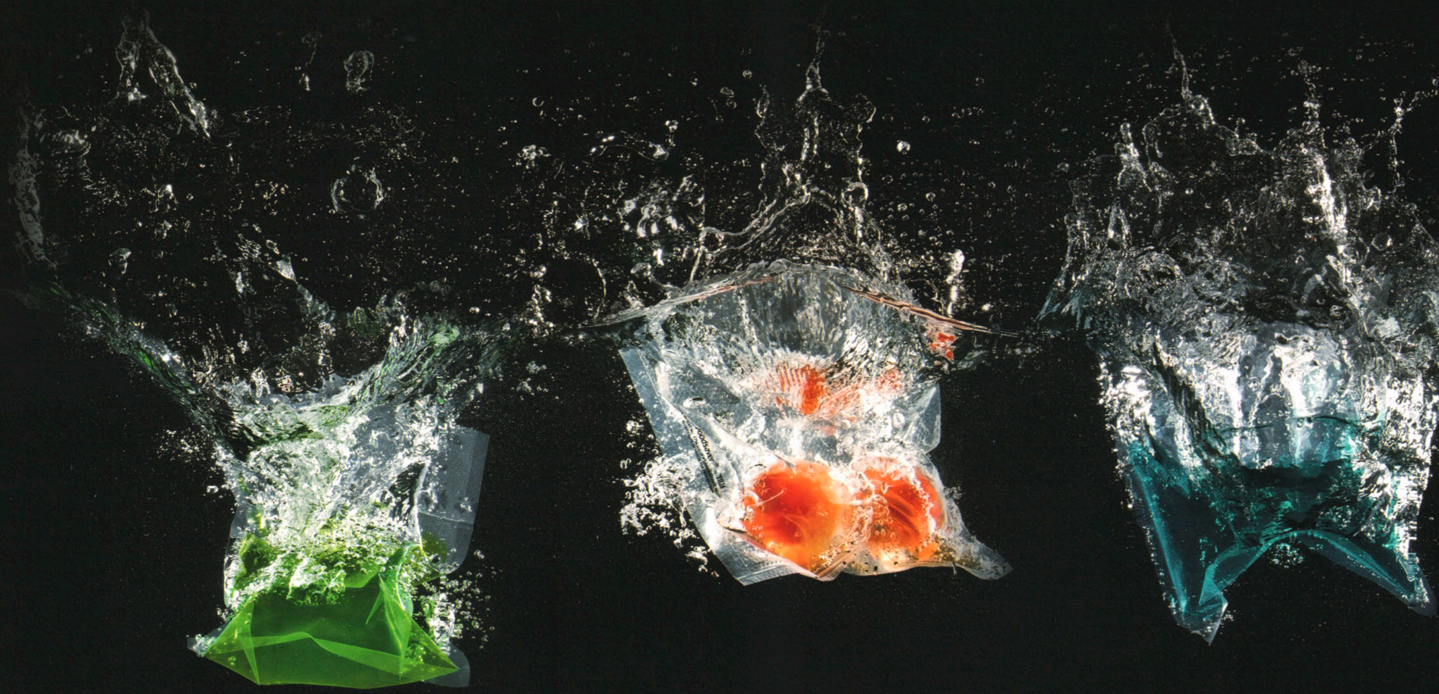
Containers for Cooking Sous Vide

The classic approach to sous vide is to use a chamber sealer to seal food inside a plastic pouch or bag. There are many other options, however, and choosing the right type of bag is nearly as important as choosing the right machine. Bags come in a wide range of dimensions and prices. Precut bags are the most useful, but you can also purchase long rolls of bag material.

Bags must keep the juices in and the water or steam out. They also must maintain their strength at high cooking temperatures, remain flexible when very cold, and prevent gases from moving in and out. Unfortunately, no single plastic has all of these characteristics.

The least expensive bags are typically made from a few layers of polyethylene-based film. Although polyethylene film provides an excellent moisture barrier, it is permeable to gases, so it allows oxygen to leak into the bag. Over time, that can create off-flavors in the food. These bags also tend to weaken at temperatures greater than 85 °C / 185 °F.

Although it's hard to tell from simple inspection, not all bags are equal. Better bags combine multiple layers of different plastics. These layers are laminated together to create a material that



Chamber-style vacuum bags come in assorted sizes and a wide range of prices. The more expensive bags remain durable when hot and cold and block out food-spoiling oxygen well.

Edge-seal vacuum bags have a waffled texture that prevents an edge sealer from sucking the bag closed while it draws the air out. Typically these bags are made from a continuous roll of material.

Retort bags are made from plastics that withstand the higher temperatures used when canning food. Special coatings create a near-perfect barrier against oxygen but increase the cost of the bag.

is strong and provides a good barrier to moisture and gas. Usually the more layers the bag has, the higher its quality—and its price. The inner and outer layers of such bags are typically made from linear, low-density polyethylene, which is strong and moisture-resistant. Sandwiched between these layers are alternating layers of other materials such as nylon, which forms a good barrier against oxygen and other gases. A sheet of resin known as a tie layer binds the layers of plastic together.

When selecting sous vide bags, check the manufacturer's specifications on the material thickness, oxygen-barrier rating, suitability for freezing, and maximum temperature rating. Avoid thin, cheap bags because they provide poor gas barriers and have weak seals that are more likely to burst. Consider whether food will be served immediately, refrigerated, or frozen in the bags. Gas impermeability is not really an important factor for immediate-service sous vide; the longer food is stored, however, the better the oxygen barrier needs to be.

When freezing food, keep in mind that many bags turn brittle when cold and therefore can easily be punctured. Use thicker bags made from less brittle plastics to help to keep this from happening.

Heat-shrink bags compress food more tightly than a vacuum alone can. Molecules aligned in the bag are stretched when cool but shrink when heated, shortening the bag to about a quarter of its initial length.

Zip-closure bags are inexpensive and available at any corner store. Although not suitable for cook-chill sous vide, they can work well in a pinch for improvising sous vide packaging.

Oven bags are larger and more durable at high temperatures than zip-closure bags, but they are more difficult to seal. Like zip-closure bags, they are not suitable for cook-chill sous vide.

How Vacuum Packing Works

Before we describe the several kinds of machines you can use to contain food when cooking it sous vide, it is important that we explain what actually happens during the vacuum-packing process. The phenomenon can be counterintuitive, and confusion about it has given rise to some myths about cooking sous vide.

We mentioned one of these myths earlier: that the food experiences a vacuum inside its bag. A **vacuum** is space containing little or no matter—not even gas. The nuts in a hermetically sealed can are in a vacuum, and when you open the can you can hear the air rush in to fill the void. But no such hiss is heard when you tear open a sous vide bag with food inside. Unlike cans, flexible bags aren't strong enough to resist atmospheric pressure, which at sea level is about 1,013 mbar / 14.7 psi. As a result, the pressure inside a sealed sous vide bag equals the pressure outside the bag.

Although fish can be quite delicate after cooking, raw fish is extremely robust—by necessity. A fish swimming at a depth of just 10 m / 33 ft experiences twice the normal pressure of the atmosphere. That pressure is far greater than any a cow will ever experience and also exceeds the force that vacuum sealing exerts on fish flesh.

If you really want food to experience a lengthy vacuum, pack it in a rigid container, then suck out the air. Even then, however, the contents won't remain in a low-pressure environment for long. Water, alcohol, and other volatile compounds will evaporate or outgas from the food, gradually filling the container with a mixture of vapors.

There is an important exception to the general rule that the pressures inside and outside a vacuum-sealed bag are the same, and this exception explains why vacuum packing can crush delicate foods such as raspberries. The exception arises for foods that contain air-filled nooks, crannies, and hollows. A plastic sous vide bag isn't elastic enough to stretch into a narrow void—such as the hollow center of a raspberry—and to apply supportive pressure after the air is removed. So the crushing weight of the atmosphere causes the berry to collapse. In special cases, this crushing can be desirable (see Vacuum Compression, next page), but usually the effect is unwanted.

One obvious way to avoid this problem when packing delicate foods is to draw the pressure down only slightly when sealing the bag, so plenty of air remains to fill any tight spots. This largely defeats the purpose of vacuum packing, however. Even a 75% vacuum during sealing leaves more than enough oxygen inside to eliminate the preservative benefits of vacuum packing. Reducing the sealing vacuum less dramatically—say from a 99.9% vacuum (1 mbar / 0.01 psi) to a 95% vacuum (50 mbar / 0.7 psi)—will not help to avoid compression damage to the food, despite assertions to the contrary. A 95% vacuum simply does not leave enough residual air pressure to fill in voids and invaginations in the food.

A better but more complex solution is modified-atmosphere packing, which is often used in commercial food packing. Oxygen-free gases like nitrogen and carbon dioxide are pumped into the vacuum chamber to replace the air that has been pumped out. The bag is then sealed with enough gas pressure inside to resist crushing. The complexity of this system unfortunately puts it beyond the capabilities of most restaurants.

Rigid containers offer a more practical alternative for chefs and home cooks when oxygen-free storage is the goal. But because heat flows evenly only through a tight-fitting package, neither modified-atmosphere packing nor rigid containers are suitable for cooking. One work-around that can help when cooking delicate pieces of meat or seafood is to stretch a few layers of thin, elastic plastic wrap around each portion before placing it in the sous vide bag. The plastic wrap adds padding that absorbs some of the uneven forces on the food after it is vacuum sealed, thus preventing it from being pinched or crushed.

Raspberries don't do well when vacuum packed because the plastic bag cannot fill their hollow centers to support them against the weight of the atmosphere.

Boiling not Crushing

Many chefs have noted that certain foods, particularly seafood and meats, seem slightly drier or have a change in texture after they have been sealed in a strong vacuum. These effects have nothing to do with being crushed; they occur because the food boils during vacuum packing.

Vacuum packing speeds evaporation of water from food—so much so that a strong vacuum can actually bring the water in the food to a boil (see Liquids in a Vacuum on page 215). By evaporating rapidly into water vapor, the expanding steam does a lot of damage to the food, even though it is not hot. Cells rupture and are pushed aside to create channels. During cooking, juices leak out of the food through these channels, drying the food and damaging its texture. If this seems a bit abstract, imagine stepping out the airlock of a space station into the vacuum of outer space and how it would feel as the water in your body boiled from exposure!

You can avoid low-pressure boiling by sealing only very cold food and by setting the pressure no lower than necessary. Keep in mind that in food at refrigerator temperatures, water begins evaporating rapidly at pressures less than 20 mbar / 0.3 psi, and it boils at 5–10 mbar / 0.1–0.2 psi. A sealing pressure of 30–50 mbar / 0.4–0.7 psi works best for nearly all foods. Pulling a harder vacuum will not tighten the packaging perceptibly; by that point, very little air is left to remove from the bag. Any marginal benefit from an ultratight vacuum is in any case quickly obliterated as soon as cooking begins. Water evaporating from the food rapidly increases the pressure in the bag: by the time food reaches 55 °C / 130 °F, the pressure in the bag is approximately 150 mbar / 2.2 psi.

When wrapping delicate food to protect it during vacuum sealing, use food-grade polyethylene film rather than cheap polyvinyl chloride plastic wrap for safety reasons (see page 206).

If the bag contains any alcohol, such as wine, then the pressure will increase even faster during cooking. At warm temperatures, ethanol evaporates even more quickly than water does.

THE PHYSICS OF

Vacuum Compression

Sometimes crushing food with vacuum sealing is exactly what you want to achieve. **Vacuum compression** has become a popular technique with chefs, but how it works is often misunderstood.

Vacuum compression works best on plant foods, thanks to a distinct feature of plant anatomy. The cells of plant tissue contain pockets of air and water called **vacuoles** (see Plants as Food, page 3·262). As the outside pressure decreases during vacuum sealing, these vacuoles act like balloons rising up through the atmosphere, and like balloons they eventually pop. The popped vacuoles cannot reinflate after the bag is sealed—no air is left in the bag—so they collapse under the weight of atmospheric pressure as soon as the sealing chamber is opened. The net result is that plant foods tend to shrink when vacuum packed. Cooks often repeat this process several times to rupture most of the vacuoles and achieve complete compression. Incidentally, this phenomenon also is the reason that infusing liquids into fruits or vegetables under vacuum compression works so well. Once the vacuoles rupture, they quickly fill with any surrounding liquid. See page 3·288 for recipes that exploit this effect.

Vacuum compression works well only with plant foods. The muscle cells in meat and seafood contain no vacuoles or large air pockets. Although meats do brine and marinate faster during vacuum compression, a very different mechanism is at work (see Brining, page 3·154).

Chamber Sealers

Large-scale commercial operations and restaurants that use sous vide cooking typically rely heavily on chamber-style vacuum sealers. These appliances are large, heavy, and expensive, but they do an excellent job and enable several novel culinary techniques.

To use a **chamber sealer**, you lay bags of food in the chamber and place their open ends on a sealing bar. After the lid is closed, a powerful vacuum pump evacuates the air. The sealing bar heats up, melting a strip of the bag and bonding it closed. The chamber then returns to atmospheric pressure and unlocks the lid. (See How to Vacuum Pack Food with a Chamber Sealer, page 218.)

One advantage of this approach to vacuum sealing is that liquids stay put. If air were to be sucked out of the bags directly, any liquids inside the bags would be pushed toward the inlet of the vacuum pump. But because the entire chamber is evacuated, the bags never collapse; the pressure pushing on the outside of the bag is nearly the same as the pressure inside the bag.

A chamber sealer enables a cook to alter food in several ways that are difficult to do otherwise, including by vacuum-assisted compression and by vacuum-assisted aeration. For more on vacuum compression, see page 3·390. Vacuum-assisted aeration is described on page 4·310.

Actually, a keen observer would notice that the bags briefly inflate a little. That short period of expansion happens because the air flows out of the chamber a bit faster than it can escape from the bag, especially once the sealing bar clamps down on the bag. This sets up a small pressure differential that causes the bags to puff slightly at first.

A second advantage of chamber sealers is their high throughput. With a powerful vacuum pump and a large chamber capable of sealing multiple bags at a time, a single machine in a busy professional kitchen can seal hundreds of bags on any given day.

Like any advanced cooking technique, vacuum sealing requires some experience to achieve proficiency. Even with practice, several kinds of problems occur regularly when food is being vacuum sealed. The bag may not seal properly, air may still be in the bag, or the food may be damaged or distorted while being sealed. We suggest solutions to these and other common problems on page 220.

Although most sealing problems are merely annoyances, a bad odor coming from a bag when it is opened should be a big concern. Bad odors can be a signal that bacterial growth has occurred during storage or cooking. Because some bacteria generate dangerous toxins, promptly discard any food in bags that smell bad when opened. Similarly, bags puffing up over time while cold may be a symptom of bacterial growth inside. (Note, however, that a bag with a poor vacuum seal may be puffy all the time.)

The exception to this guidance is for cruciferous vegetables such as Brussels sprouts, cabbage, cauliflower, kale, and turnips, which naturally emit sulfurous gases during storage. Typically, these vegetables should be blanched before cooking, then either frozen for storage or cooked very quickly (see page 3·286). If their odor becomes a problem, it may be better to cook them some other way.

Bags containing alcohol normally inflate when heated because the temperature of the alcohol is near its boiling point (70 °C / 158 °F). Even bags without alcohol can puff up when they get very hot simply because the residual air, water vapor, and other volatile materials in the bag expand when heated. If a bag is puffy or inflated while at room temperature or lower, however, it may contain harmful bacteria and should be discarded.

Vacuum packing food is not difficult, but it is important to remember that generally *only cold foods should be sealed*. Once you have removed roughly 80% of the air from the bag, the boiling point of water is at 60 °C / 140 °F and falling. If the food in the bag is hotter than that, it will begin to boil in its own juice (see next page).

It is possible to tightly seal hot liquids if you allow them to boil in the chamber long enough for the pump to remove nearly all the air, but we don't recommend this approach. The result is usually a soft seal. Although the seal tightens as the food cools, it never becomes as tight as it would have if the food were sealed when cold. Air remaining in a bag can cause it to float in the water bath and can lead to uneven cooking of the food inside.

THE PHYSICS OF

Liquids in a Vacuum

When a vacuum chamber lowers the pressure around a bag of food, it also decreases the boiling point of water (see chapter 6 on The Physics of Food and Water, page 1·292). This phenomenon occurs naturally at high elevations but is much more dramatic during vacuum sealing. At a typical sealing pressure of 23 mbar / 0.3 psi, for example, the boiling point of water is only 20 °C / 68 °F, which is also the boiling point at an altitude of roughly 23,000 m / 75,000 ft. If you try to vacuum seal something that is warmer than this, the water in the food will start to boil.

The interaction of boiling and pressure is even more complicated than that. On the one hand, the boiling water temporarily prevents the pressure from dropping further because the vacuum pump must suck out the water vapor coming off the food. The pressure decreases further only once all (or nearly all) of the water has boiled away. On the other hand, the very act of evaporation cools the food in the same way that evaporating sweat cools a hot body. So as more vapor boils off the food, the food gets colder, and that in turn lowers the pressure inside the bag, which decreases the boiling point further—and tends to accelerate the boiling!

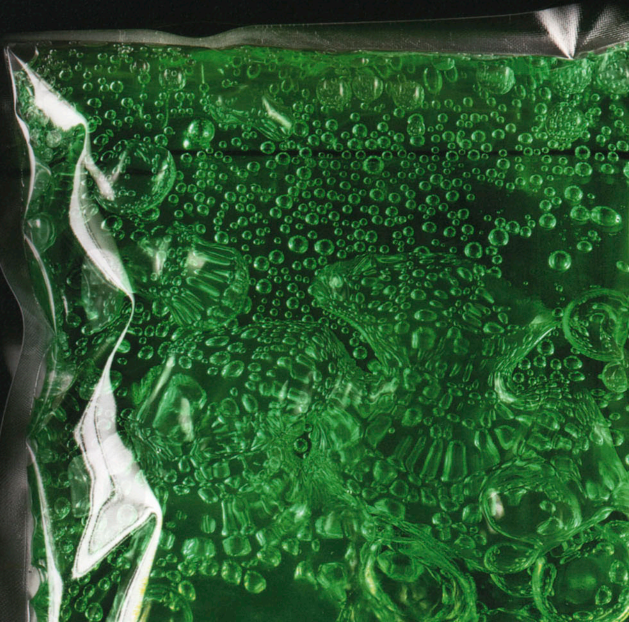
This phenomenon can be a nuisance because it means that food must be cooled before sealing to achieve a firm seal. But it can also be put to use if you need to rapidly cool and dehydrate food. Vacuum drying allows liquid to boil off the surface of the food while simultaneously cooling the food. It leaves a dry surface and can be very handy for making food crispy (see Vacuum Drying, page 433).

Frequent boiling inside a vacuum-sealing chamber can damage the vacuum pump. Moisture will emulsify into the lubricating oil in the pump over time, turn the oil into a thick sludge, and degrade the pump's performance. Change the oil frequently to avoid this problem. Alternatively, some vacuum sealers have an accessory cyclone separator between the chamber and the pump. The separator literally spins the moisture from the air and drains it away before it can get sucked into the pump.

How a Vacuum Is Like a Mountain

Pulling air out of a container is like carrying it up a mountain: both actions reduce the air pressure and, in so doing, reduce the temperature at which water and other liquids boil. If 69% of the air is removed from a sous vide bag, the contents will cook as if your kitchen were at the summit of Mount Everest!

Vacuum	Boiling point of water		Pressure		Equivalent altitude	
(%)	(°C)	(°F)	(mbar)	(psi)	(m)	(ft)
0.0	100	212	1,013	14.7	0	0
31.0	90	194	701	10.2	3,000	9,840
53.3	80	176	474	6.9	5,960	19,600
69.2	70	158	312	4.5	8,900	29,200
80.3	60	140	199	2.9	11,800	38,700
87.8	50	122	123	1.8	14,600	48,000
92.6	40	104	74	1.1	17,400	57,000
95.8	30	86	42	0.61	20,100	66,000
97.4	20	68	23	0.33	22,700	74,600
98.0	15	59	17	0.25	24,000	78,600
98.8	10	50	12	0.17	25,300	82,900
99.2	5	41	9	0.13	26,300	86,200
99.4	0	32	6	0.09	27,600	90,600

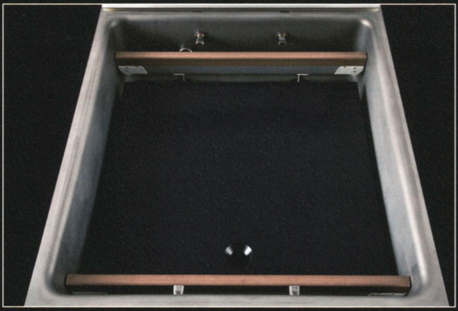


Optional Features of Chamber Sealers

Chamber sealers are expensive, so it's worth exploring the features available and selecting one that has the features that match your needs. Here are some of the options we have found to be especially useful.

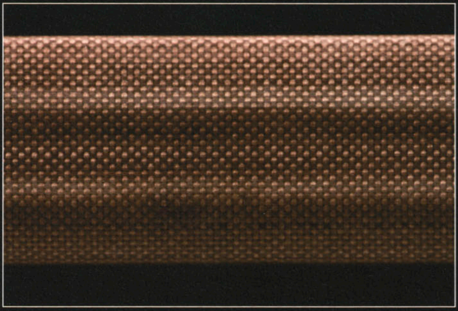
Recommended feature	Typical alternative	Advantage
dual seal bars	single seal bar	doubles the throughput of the machine
double-seam sealing wire both above and below	single-seam sealing wire above only or below only single-seam wire both above and below double-seam wire below only	provides a more secure seal and allows the use of specialized, thicker retort bags
digital pressure gauge	analog gauge and timer	more reliable way to seal bags consistently
programmable settings	not programmable	provides additional control and convenience
soft air release	uncontrolled pressure release	protects delicate foods from decompression damage
external vacuum port	no external port	provides option of using rigid containers
gas injection	vacuum seal only	provides option of preserving delicate foods under inert gases
cyclone separator	unfiltered vacuum line	protects the vacuum pump from water and debris in the vacuum line

Some chamber-style machines have a digital pressure gauge, which provides an accurate way to turn the pump off at a preselected pressure. Certain models also have a convenient feature that allows you to save combinations of vacuum settings and sealing times as programs.



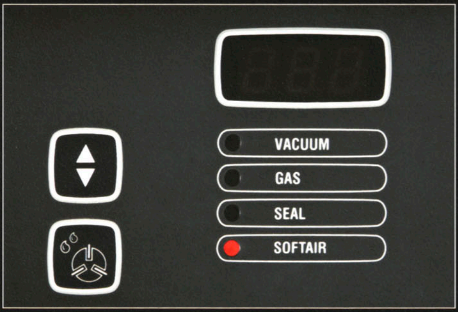
Dual seal bars

The reason to pay a little extra for dual seal bars is simple: they double the capacity of the machine. Typically, the number of bags you can seal each time you run the machine determines how many bags you can seal per hour. A busy kitchen could easily seal hundreds of bags a day, and having a second bar could effectively cut the time involved in half at only a small incremental cost.



Double-sealing wires above and below

Each sealing wire is encased in a tube made of silicone film. A small puff of air inflates the tube, pressing the wires tightly against the bag. An electric pulse then heats the wire and seals the bags closed. Sealing wires come in many configurations: thick and thin, single and double, wires on the lower sealing bar only or on the upper bar as well. Choose double wires if you can because a double seal reduces the odds of a bag opening unexpectedly. Having wires both above and below the bag works best when using the thick, multilayered bags designed for pressure-cooking or freezing.



Soft air release

Vacuum-sealing drops the air pressure to about 25 mbar / 0.36 psi. If the vacuum port opens all at once, a shock wave will form as the pressure shoots back up to atmospheric pressure, a change of nearly 1,000 mbar / 15 psi. That change is substantial: a fast shock wave of just 700 mbar / 10 psi does severe damage to reinforced concrete! No chamber sealer equalizes the pressure quickly enough to generate such force, but the shock can crack eggs and damage food in microscopic ways that aren't apparent until after cooking. Soft air release increases the pressure gradually to protect delicate ingredients like foie gras. Overriding this feature can be handy for performing interesting culinary tricks such as vacuum compression (see page 3·390).

External vacuum port

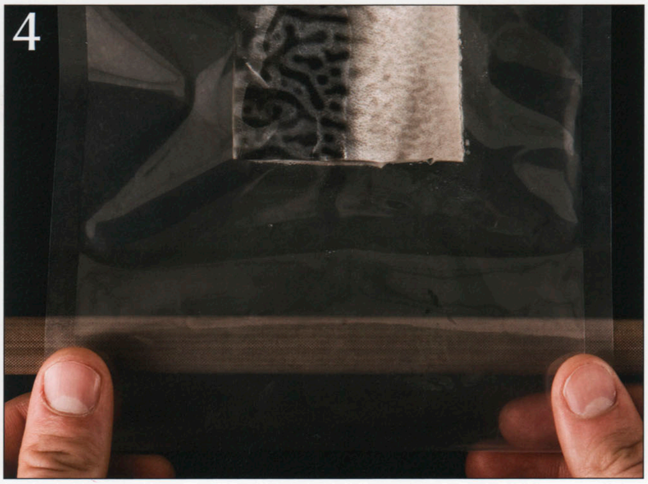
When you seal delicate items such as berries or mushrooms in flexible plastic bags, you may be dismayed to find that the weight of the atmosphere crushes them as soon as the chamber is ventilated. If the sealer has an external vacuum port, you can connect the vacuum pump to a special rigid container that has an airtight lid. A one-way valve on the lid allows the sealer to evacuate the container, which preserves the freshness of the food without crushing it. An external port is not an essential option, but it's nice to have.

Gas injection

Starve fruits and vegetables of oxygen long enough, and they die. This effect obviously poses a problem for vacuum packing. One solution is to replace the air with a different blend of oxygen, carbon dioxide, and nitrogen. Produce at the peak of ripeness will then survive, but its respiration will be slowed, thus preserving more of the sugars and starches inside. To use a modified atmosphere, your sealer must have a gas injection port. Modified atmosphere packing adds substantial complexity to the vacuum packing process, which is why few chefs have experimented with the technology.

HOW TO Vacuum Pack Food with a Chamber Sealer

Professional kitchens that have embraced sous vide cooking as a way to deliver consistent quality usually rely heavily on chamber sealers. The speed, efficiency, and flexibility of these appliances justify their steep cost. Although using a chamber sealer is straightforward, spills and accidents will happen, so it's important to use good hygiene. Many foods, both raw and cooked, will pass through the chamber, so be sure to package foods properly and sanitize the appliance regularly to reduce the risk of cross-contamination.

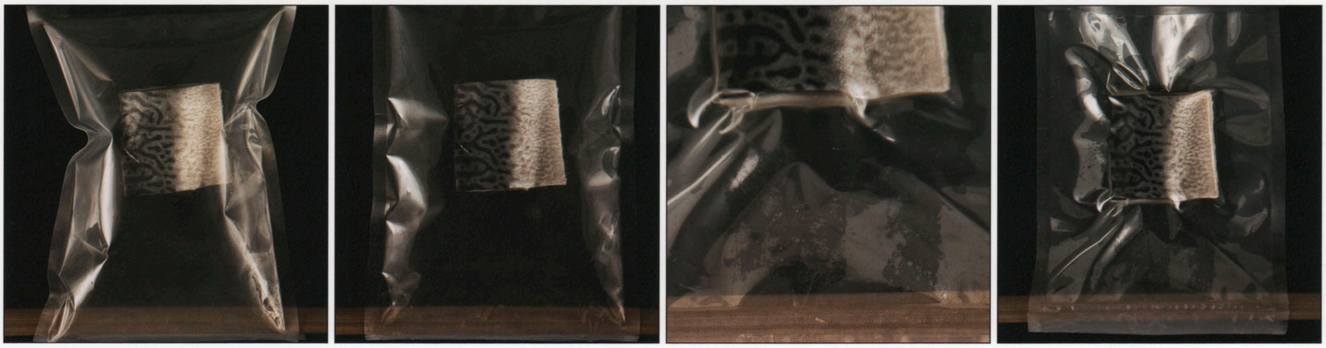


1 **Fill the bag.** Place the food into a bag large enough to allow you to flip the top 5–8 cm / 2–3 in of the bag inside out. This technique improves hygiene and ensures there will be enough clean material at the top to make a secure seal; it does not damage the bag, as sometimes asserted.

2 **Set the vacuum level (not shown).** For most solid foods, 30–50 mbar / 0.4–0.7 psi produces a hard seal. Fragile foods that can be damaged by the contracting bag can be sealed for storage at 200–500 mbar / 3–7 psi.

3 **Adjust the sealing time (not shown).** The sealing time determines how long the sealing wire stays hot. Thicker bags and bags made of more heat-resistant material need longer sealing times.

4 **Place the bag in the chamber.** Unfold the top of the bag, lay the bag flat in the chamber, seat its top on the sealing bar, and tuck the open end of the bag under the bar. Double-check that the edge of the bag does not protrude from the chamber, then close the lid firmly.



5 **Monitor the sealing process.** The vacuum should engage automatically.

a. Because air rushes out of the chamber more quickly than it escapes the bag, the pressure will at first be slightly higher in the bag, which will cause it to puff up. Too much swelling can pull the ends of the bag off the sealing bars.

b. The pressure inside the bag will equalize as air gradually leaks through the open end. Use the vacuum gauge to monitor the pressure inside the chamber.

c. When the vacuum reaches the preset level, wires in the sealing bars will bond the sides of the bag together.

d. The chamber will then refill with air, and atmospheric pressure will push the bag tightly around the food.

VARIATION: Vacuum Packing Liquids with a Chamber Sealer

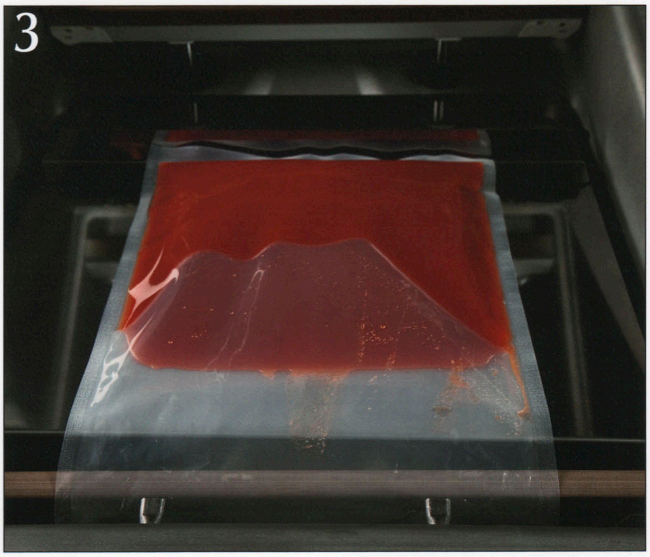
1 **Fill the bag.** Placing the top 5–8 cm / 2–3 in of the bag over a cylinder makes it easier to fill without spilling.

2 **Set the vacuum level and sealing times (not shown).** For cool liquids, use a vacuum of 50 mbar / 0.7 psi to help prevent boiling in the bag that can foul the vacuum pump (see Liquids in a Vacuum, page 215).

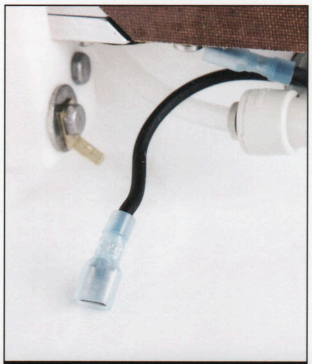
3 **Place the bag in the chamber.** Laying the fluid-filled bag on a ramp will help prevent it from leaking during the sealing process. The remaining steps of the technique are the same as for solid foods.

1

3



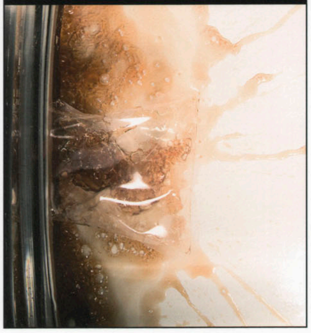
Common Problems When Vacuum Sealing Foods



Problem	Possible cause	Solution
The vacuum pump ran, but the bag did not seal.	The opening of the bag was not seated on the sealing bar properly.	Make sure that enough material is left out so the opening of the bag can sit flat across the sealing bar, with the open end folded over and tucked behind the bar.
	The sealing bar wire was not plugged in.	Most sealing bars can be removed for cleaning. Make sure that the sealing wire is connected and tight.
The food was not sealed tightly enough.	The vacuum was set to the wrong level.	Check the vacuum settings.
	The food was too warm.	Chill the food, and consider repackaging it.
	The bag had a slow leak.	Check the integrity of the seal and the bag. Repackage if necessary.
The shape of the food was ruined.	The vacuum level was too high.	Delicate items may need to be sealed at a higher pressure (in a weaker vacuum).
	The food was compressed by the packaging.	If packing for storage and not cooking, use a rigid container. Otherwise, wrap the food with thin, elastic plastic film to provide extra support for the desired shape while cooking the food in the bag.
The bag burst, or the seal failed during cooking.	The temperature was too high for the packaging material.	Check the maximum temperature rating of the bag. Some materials become weak at temperatures near 70 °C / 158 °F and fail at temperatures greater than 80 °C / 176 °F. If this is the case, use a different kind of bag.

continued

Problem	Possible cause	Solution
The bag sealed tightly, but now air has gotten back in.	The seal was bad.	Wrinkled or dirty seals often fail and slowly let air back in. Cut off the top of the bag, and reseal it.
	The bag was punctured.	Bones and other sharp items can puncture the bag. Wrap the bone or sharp edge in protective padding such as plastic wrap. Alternatively, use a heavier bag.
	Anaerobic bacterial growth occurred.	Throw out the food. The bag has not been properly refrigerated, and anaerobic bacteria have begun to grow and produce excess gas.
When the bag was opened, it emitted a bad odor.	Bacterial growth occurred.	Throw out the food. The food was not properly refrigerated or was cooked at too low a temperature for too long.
After cooking, the food was too dry, or the texture changed.	Water in the food boiled during vacuum sealing.	Cool the food to lower temperatures before sealing. Use a higher sealing pressure (lower vacuum).
The bag fogged during cooking.	The seal was bad, or the bag was ruptured.	Resealing the food in a new bag may be possible.
The plastic became opaque during cooking.	The bag material was unsuitable for the cooking temperature.	Use a different kind of packaging material. Many plastics become opaque when heated beyond their useful temperature.
During sealing, the bag exploded in the chamber.	The edge of the bag was sticking out of the chamber.	Check bag placement before closing the lid. When the edge of the bag is outside the vacuum chamber, no air can escape. As the pressure in the chamber drops, pressure in the bag increases until the bag bursts.



Choose a bag large enough to reach all the way across the sealing bar and into the vacuum reservoir when the bag is full.

Edge Sealers

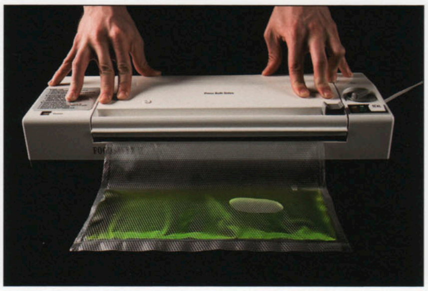
Edge sealers are a lower-priced alternative to chamber sealers. For the savings in cost, you have to trade some functionality, however. The vacuum pump in an edge sealer is not nearly as powerful as the one in a chamber sealer, so the packages cannot be sealed as tightly. An edge sealer also removes air differently: it sucks it out of the open end of a specially textured bag. This approach works poorly when sealing liquids because they tend to get sucked into the vacuum pump as the bag collapses. Finally, edge sealers can only use bags that have a special waffle texture. The waffle texture ensures that air does not get caught in pockets around the food. It also prevents the opening of the bag from being sucked closed during the vacuum-sealing step.

The special texture makes the bags somewhat expensive, but they are generally well constructed. Because they are laminated from five layers—four inner layers made of polyethylene and an outer layer of tough, gas-impermeable nylon—the bags are quite durable and particularly good for storing frozen food.

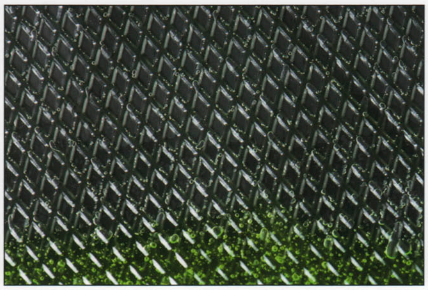
Adding ice is the easiest way to include water in an edge-sealed package without flooding the vacuum reservoir.

COMMON PROBLEMS WHEN SEALING FOOD IN AN EDGE SEALER

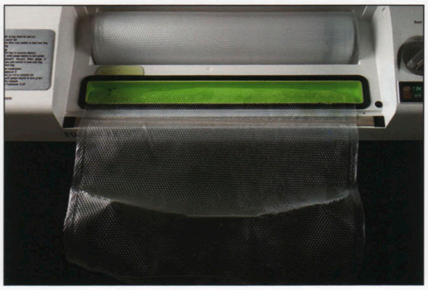
As with chamber sealers, some common problems tend to occur with edge sealers. Most of the problems and solutions listed for chamber sealers in the table on page 220 apply to edge sealers as well. But edge sealers are also uniquely susceptible to having liquid or debris sucked from the bag into the vacuum pump reservoir. This problem can cause a poor seal or prevent the pump from removing all of the air in the bag. As a preventive step, freeze or otherwise solidify the liquid before adding it to the bag and sealing it. Alternatively, use the optional rigid containers.



We do not recommend using an edge sealer to vacuum pack liquids.



Both air and liquids get sucked out through channels in the waffle-textured bags.

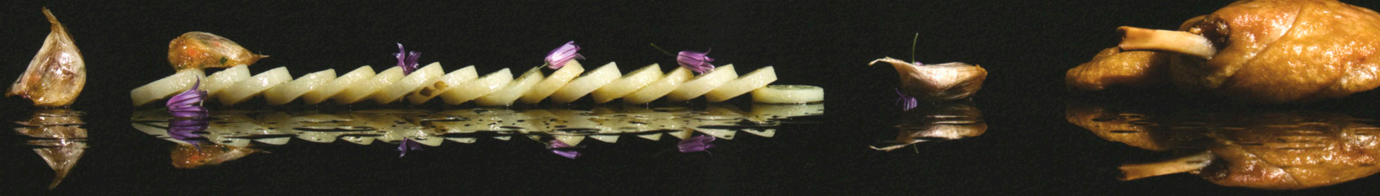


Instead of being sealed in the bag, the liquid creates a mess in the machine.

HOW TO Vacuum Pack Food with an Edge Sealer

Edge sealers offer an inexpensive alternative to costly chamber sealers and bring sous vide packing within reach of budget-conscious cooks. Frugality imposes some trade-offs, however. An edge sealer won't seal as tightly as a chamber sealer, and it requires specially textured bags. Be sure to freeze or otherwise solidify liquids before sealing.

Sous vide packing requires only a fraction of the fat used in traditional approaches, which makes dishes such as duck confit more practical (see page 3·178).

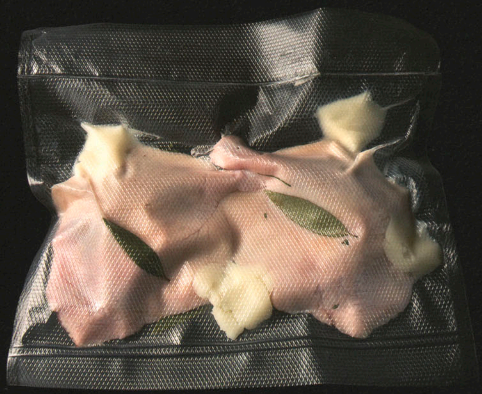


1 **Make a bag (not shown).** Cut a suitable length of waffle-textured plastic from a roll by using the built-in cutting blade. Then use the sealing bar to close one end.

2 **Fill the bag.** Flip the top 7.5 cm / 3 in of the bag inside out, and fill the bag with food. Liquids should be frozen or solidified before adding them so they do not get sucked into the vacuum pump.

3 **Place the bag in the edge sealer.** Unfold the lip of the bag, and lay the open end over the sealing bar and into the vacuum reservoir. Place the textured side down to prevent the bag from curling out of the vacuum reservoir.

4 **Close the lid (not shown).** To prevent wrinkles and a poor seal, stretch the opening of the bag flat along the sealing strip before closing the lid and engaging the vacuum pump.



5 **Double seal if desired.** For extra security, place a second seal about 5 mm / ¼ in above the first seal.

6 **Clean the machine (not shown).** Both for hygiene and to extend the life of the appliance, wipe out any liquid or crumbs in the vacuum reservoir and sanitize it before storing the sealer.

Impulse Sealers

An impulse sealer is another low-cost alternative to a chamber sealer. The main downside to an impulse sealer is that it only seals; it does not remove air from the packaging. An impulse sealer has essentially the same set of sealing bars that one might find in a chamber sealer, except that they are mounted on a simple frame.

Impulse sealing is acceptable for immediate-service sous vide, which does not require keeping oxygen away from food. To prevent the bag from floating, the air can be removed by pushing down on the bag to squeeze the air out before sealing. Alternatively, dip the bag in a sink full of water to displace the air before using the impulse sealer to close the bag.

Even after taking such precautions, you'll find that these bags have a tendency to float. If that happens, simply anchor the bag underwater with something heavy. Sous vide cooking in a combi oven, steamer, or other equipment works just fine with impulse-sealed bags.

Both conventional sous vide bags and shrink bags work with impulse sealers. Shrink bags must be heated (and thus shrunk) before sealing, however. Otherwise the bag will swell like a balloon as it shrinks. Even if it doesn't burst, a swollen bag surrounds the food with air, which results in uneven cooking.

Impulse sealers can be handy for making separate compartments in a bag that is then vacuum packed. This technique can be extremely useful for sealing several components of a dish together in one package, simplifying service, and ensuring that everything is cooked just when it needs to be.

Although impulse sealers have limited uses, one excellent use is dividing a bag into individual compartments to keep different components of a dish neatly organized for reheating during service. The entire assembly can be vacuum packed by using a chamber sealer, then compartmentalized with an impulse sealer.

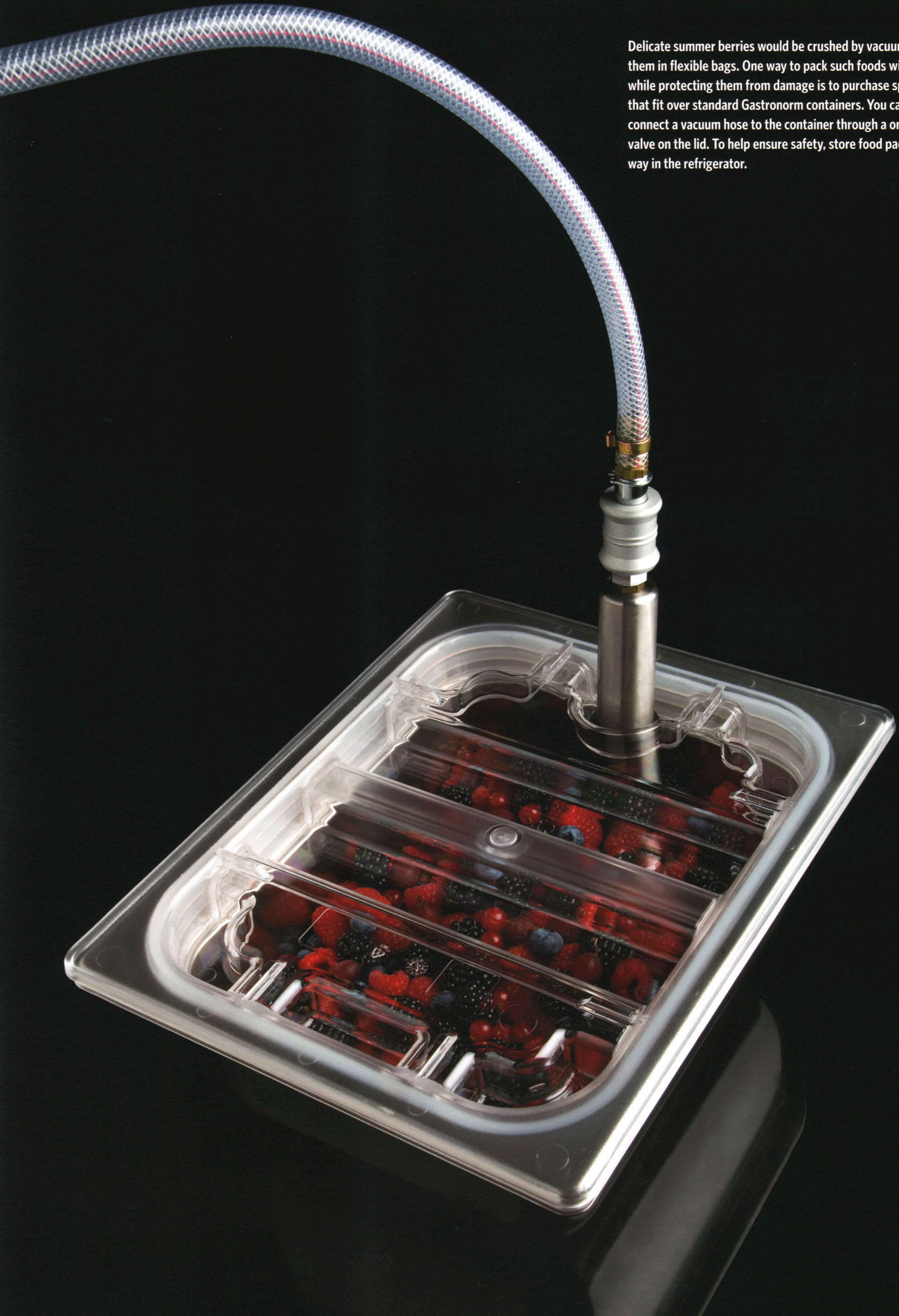
If you really want food to experience a lengthy vacuum, vacuum-pack it in a rigid container. Even then, however, the contents won't remain under very low pressure for long. Water, alcohol, and other volatile compounds will evaporate or outgas from the food, gradually filling the container with a mixture of vapors.

Rigid Containers for Storage

Rigid containers are less useful for sous vide cooking than bags because the container takes up space. Also, food tends to cook less evenly in a container than in a bag. But rigid containers can be quite useful for vacuum storage and are available in various shapes and sizes for most edge sealers. Special lids are made for standard Gastronorm hotel pans, which can be used with some chamber sealers to create rigid vacuum containers.

Unlike a sous vide bag, a rigid container maintains a vacuum after packing. That is, the food inside remains under very low pressure. This environment can be just what you want for storing fruits and vegetables, but the container must be sturdy enough to resist atmospheric pressure in addition to the normal stresses of handling. Although generally it is important to refrigerate or freeze vacuum-sealed foods after cooking, it is not a good idea to freeze food in a rigid container. Expansion and contraction of the plastic during freezing may break the vacuum seal and can eventually ruin the container.

Special rigid containers made for use with edge sealers can be helpful to have on hand, especially when sealing fragile and expensive ingredients such as morels. Unlike vacuum-packed bags, these containers can withstand atmospheric pressure. Keep in mind that even though the food is in a vacuum, anaerobic bacteria on the surface will continue to grow unless the container is refrigerated or frozen.



Delicate summer berries would be crushed by vacuum sealing them in flexible bags. One way to pack such foods without air while protecting them from damage is to purchase special lids that fit over standard Gastronorm containers. You can then connect a vacuum hose to the container through a one-way valve on the lid. To help ensure safety, store food packed this way in the refrigerator.

SOUS VIDE EQUIPMENT

For more on the science of the rotisserie, see Roasting, page 28. For more on combi ovens and water-vapor ovens, see chapter 8 on Cooking in Modern Ovens, page 150.

In the Middle Ages, the chef of an estate would hire a "spit boy" to turn a large portion of meat by hand beside a fire. If you have ever seen (as we have) a chef press a raw steak into a hot frying pan for a few seconds, take it out for a moment to cool, flip it over, and repeat this cycle again and again until the center of the steak is perfectly cooked, then you have seen a modern version of the medieval rotisserie. The idea is to heat the meat in intense pulses that are short enough that no single pulse overcooks the surface, yet strong enough that cumulatively they create a crispy crust and a juicy, perfect center. Unfortunately, this process takes hours, which makes it wildly impractical to do in a busy kitchen.

Modern chefs are blessed with a wide range of choices in sous vide cooking equipment that can produce results that are as good as or better than those of any spit boy—and can do so more reliably and nearly automatically. Whereas food on a rotating spit feels widely varying pulses of heat, the same ingredients in a sous vide cooker are bathed in uniform warmth, and the temperature is continually monitored and controlled to a fraction of a degree.

The gear for cooking sous vide can be as affordable as a jerry-rigged crock pot or as foolproof (and expensive) as an industrial process controller. Water baths of various kinds are the most common tools for cooking sous vide, but combi ovens, water-vapor ovens, and even autoclaves are also used. Each has its advantages and disadvantages, as summarized on page 232.

A digitally controlled immersion circulator has fast become a feature of the modern professional kitchen. This and similar equipment give cooks unrivaled control over cooking.

Controlling the Temperature

The defining feature of sous vide cooking is the tight control of temperature it offers—not, as commonly cited, the use of vacuum packaging. The key element that enables such accurate control is a feedback loop: a thermal sensor immersed in the water or humid air near the food and connected to a heating element. You have a system like this in your oven: it's called a **thermostat**. Whereas your oven thermostat probably allows the air temperature to vary by at least 10 °C / 18 °F, a sous vide cooker can maintain temperature to within about 2 °C / 4 °F—and very good units will stray less than 0.5 °C / 1 °F.

Two quite different types of feedback loops are used in sous vide cookers. The less expensive, less accurate kind works much like a thermostat. It is called a **bang-bang controller** because it switches on—bang—when the thermometer reads a bit below the target temperature, then switches off—bang—when the reading exceeds the set point. Because it can run the heating element only at full power or not at all, a bang-bang controller inevitably causes the bath temperature to oscillate a bit over and then under the set point (see Controlling Bath Temperature with Bang-Bangs and PIDs, next page). The temperature does not swing nearly as wide as it does for food on a rotisserie, but it varies enough that the outer portions of the food can become overcooked.

A different kind of controller solves this problem by varying the amount of heating power it applies to the bath. Called a **proportional-integral-derivative controller** (**PID** controller for short), this device is one of many examples of laboratory technology that has entered the modern kitchen. A PID controller uses a small microprocessor to constantly evaluate and manage the difference between the current measured temperature and the set point. When the bath is much cooler than the target temperature, the PID supplies lots of heat; as the temperature converges on the set point, the controller throttles the heat flow back to a trickle. The heat output is, in other words, proportional to the difference in temperature—hence the P in PID.

Another way that a PID controller avoids overshooting or undershooting the target is by monitoring how fast the temperature of the bath is changing. In mathematical terms, a rate of change is called a **derivative** (the D in PID). Tracking the derivative of the temperature enables the PID to anticipate where the bath is headed and to adjust the heater power accordingly.

The proportional and derivative controls let a PID hit its set point with great accuracy, but the controller must also combat the tendency of the temperature to drift away from the target. To do this, the controller measures the small temperature error every so often and adds the errors over time. The mathematical term for that sum is the **integral** of the temperature difference (the I in PID), and by tracking it the controller compensates for the drift.

For a PID controller to work properly, it must be tuned to match the characteristics of the bath, heating element, and temperature sensor to which it is connected. PIDs that are built into water baths or other equipment are tuned at the factory, although they occasionally need calibration.

Many manufacturers of immersion circulators have gone beyond bang-bang and PID controllers to create temperature control systems that combine PID control with so-called fuzzy logic or neural networks. Although no more accurate than a well-tuned PID controller, these controllers adapt to changing circumstances without requiring recalibration. This capability makes it possible to move the immersion circulators among baths without losing temperature control and stability.

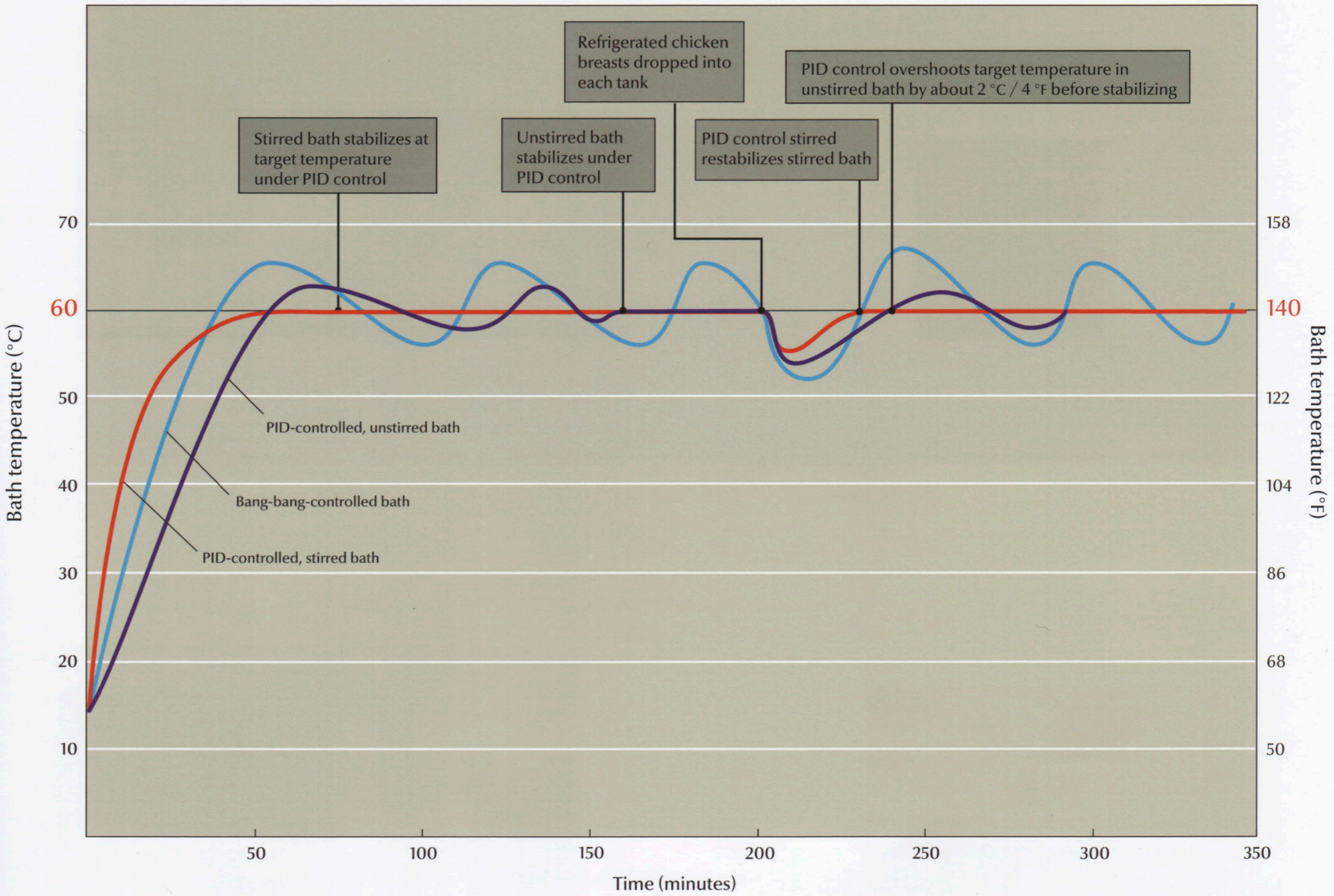
High-end PID and PID-like controllers often offer additional features that we find useful, including programmability, alarms, and temperature logging. A programmable PID helps with multistage cooking. For example, you might want to tenderize a tough flat-iron steak by cooking it to 50 °C / 122 °F and holding it there briefly to accelerate enzymatic activity before increasing the temperature of the bath to the final cooking temperature. A programmable PID can automate that process. When cooking food for very long periods of time, sometimes days, you can use a PID with a data logger or alarms to check that the bath never inadvertently cools to dangerous temperatures, as might occur during an overnight power outage, for example.

Regardless of which variety of temperature control you use, it's important to periodically calibrate the bath's internal thermometer. Simply use a reliable, hand-held thermometer to check the bath at several different temperatures. Check the manual or contact the manufacturer for instructions on how to adjust the calibration if needed.

Controlling Bath Temperature with Bang-Bangs and PIDs

The temperature controller used on a water bath can affect cooking quality noticeably. When cooking food sous vide to a target temperature (straight black line), a bang-bang controller always turns the heat either fully on or off. This causes the bath temperature (light blue curve) to overshoot the set point and then oscillate around it. During cooking, each oscillation overcooks the food more.

A PID controller adjusts the temperature more intelligently, whether the bath is stirred (red curve) or unstirred (purple curve). When cold food plunges into the bath, a PID-controlled bath will recover more quickly and with less overshoot.



This add-on PID controller is made to be used with "dumb" devices like crock pots and rice cookers; it gives them the "smarts" to control temperature accurately. Immersion circulators and water baths have similar control logic circuits built into them.

SOUS VIDE COOKERS

Although the water bath is fast becoming a standard tool in the modern professional kitchen and the icon for sous vide cooking, it is not the only choice, nor always the best choice, for cooking sous vide. A number of other equipment options offer appealing combinations of features and price points.

Noncirculating water bath

Cost: less expensive

Pros: easy to clean. More usable volume than an equivalent circulating bath

Cons: develops hot and cold spots more easily than a circulating bath. Shares the power limitations of circulating baths

Circulating water bath

Cost: moderately expensive

Pros: very accurate temperature control and very common among chefs who frequently cook sous vide

Cons: heating/circulating unit takes up bath space. Usually limited to 1,800 watts, enough to evenly heat bath volumes only up to 30 liters / 32 quarts

Water-vapor oven

Cost: moderately expensive

Pros: available with very large capacities. Capable of higher temperatures and variable humidity

Cons: heats small portions slower than a water bath does. Maximum temperature is lower than that of a combi oven. Lacks the sophisticated programs of some combi ovens

Combi oven

Cost: very expensive

Pros: very large capacity. Capable of very high temperatures, variable humidity, even direct steaming. Some have sophisticated cooking programs

Cons: less accurate temperature stability than water baths or water-vapor ovens at temperatures below 60 °C / 140 °F. Complex installation requirements

For more on cooking sous vide with a pressure canner, see Canning, page 75.

Pressure cooker or pressure canner

Cost: inexpensive

Pros: capable of increasing core food temperature to temperatures greater than 100 °C / 212 °F. Pressure canners are suitable for canning

Cons: pressure and cooking time must be controlled manually

Autoclave

Cost: very expensive

Pros: fully automatic control of pressure/ temperature and cooking time. Available in a wide range of sizes. Suitable for canning. Can reach 140 °C / 284 °F, which is a higher temperature than most pressure cookers can reach

Cons: useful for cooking at temperatures only above 100 °C / 212 °F. Food must be packaged in a jar or retort pouch

PID controller added to an existing appliance

Examples: PID-controlled crock pot or rice cooker, warming drawer, or oven

Cost: inexpensive

Pros: much less expensive than dedicated water baths or circulators

Cons: Because there is no pump to circulate the water, this cooker has less even heat flow than many alternatives. This drawback can be remedied by adding an aquarium air pump and bubbler

Pot on the stove

Cost: very inexpensive

Pros: uses equipment already in the kitchen

Cons: without a temperature control loop, it is very hard to adjust the temperature accurately, so this can work only when cooking times are limited

Controlling Water Circulation

Less expensive sous vide cookers, including those improvised from other kinds of cooking equipment (see page 240), generally heat a bath of still water. In some baths the heating element is immersed, but more commonly it sits beneath an insulated, double-walled pot. That latter arrangement has its advantages: the pot has no hard-to-clean crannies, and the unexposed heating element is less easily damaged. This design includes some laboratory water baths, called unstirred water baths. It also includes some consumer sous vide baths such as the Sous Vide Supreme (see page 236).

Such noncirculating baths have a substantial disadvantage, however. They rely on natural convection to even out any temperature differences from the top of the water to the bottom. This approach can work reasonably well for small, well-separated bags of food with lots of space around them. When the bath gets crowded and the food is large compared with the bath size, water does not circulate well. Cold spots can develop, and the food will not cook evenly. Even worse, if a lot of water evaporates, bags may touch hot spots on the bottom, which can melt the bag and scorch the food.

Circulating baths, also called **stirred baths**, avoid these problems by pumping the water to promote rapid circulation and uniform heat distribution to all parts of the bath. When working with a large or crowded bath, you can connect a hose to the pump outlet so that it transports hot water to a far corner of the bath, thereby creating stronger circulation to overcome hot and cold spots.

There are two basic approaches to circulating water baths. One is to integrate the heater and the control unit within an insulated tank. This type is usually called a dedicated water bath or a stirred water bath. The other approach is to have the same heater and control unit made as a module that can be attached to any sort of water tank or container. This second type, usually called an **immersion circulator**, almost always has a built-in pump.

Each has its advantages and disadvantages. The dedicated water bath can have an insulated tank, which heats up faster and is more energy efficient than the immersion unit. The clip-on immersion circulator can be attached to all sorts of water containers and thus is more versatile, but when it is used with an uninsulated tank, there can be problems in maintaining temperature.

Just because you can mount a circulator on an enormous stock pot doesn't mean it's a good idea. Most circulators have a maximum heating power of about 1,000 watts, and none delivers more than 1,800 watts if it has been designed for a standard 120V, 15 amp North American outlet, or 2,400 watts if running on a 240V, 10 amp European outlet. Under ideal circumstances, this is enough power to heat up to 20–30 liters / 21–32 quarts of water—but only if you cover the top and have considerable patience. If your bath is poorly insulated and uncovered, a low-power circulator may not even be able to maintain the cooking temperature. Large metal stock pots, for example, lose heat rapidly by evaporation and by conduction through the sides of the pot. With an underpowered heater or circulator, this heat loss can quickly lead to hot and cold spots

Just because a lot of food can fit in a bath doesn't mean that it is a good idea. Food packages jammed together will impede convection (made visible with a red dye) and allow hot and cold spots to develop. These cause the food to cook unevenly. In this case, the left side of the bath is not getting enough circulation, even with a powerful pump driving the flow. There is just too much food in too little bath.

and inconsistent cooking. Large pump-circulation systems use higher voltages and bigger electrical circuits to heat several hundred liters of water for the biggest and busiest of kitchens.

Whatever type of water bath you use, take care not to overcrowd it with food. There is no point in cramming more food into a bath if it produces inconsistent results from the inevitable hot and cold spots. Choose a bath that is the appropriate size for the job.

In addition, whenever possible keep your baths covered with something: a hinged lid, the lid of a hotel pan, aluminum foil, plastic wrap, even Ping-Pong balls. A lid improves heating performance and limits evaporation. That is especially important for immersion circulators, which tend to overheat and shut down if the water level falls enough to expose the heating element—a very inconvenient experience if it happens in the middle of the night, two days into a slow braise!

Circulating water baths designed to be plugged into a standard 120 V, 15 A North American outlet are generally limited to a volume of 30 l / 32 qt at most. Larger baths need more power than the electrical circuit can supply to keep the temperature even and stable.

WHAT TO LOOK FOR IN A SOUS VIDE WATER BATH

Water baths can be divided into two groups: those that stir the water mechanically and those rely instead on natural convection to spread the heat and even out the temperature. Of the two kinds, noncirculating baths tend to be less expensive and can be a good choice for consumer-level cooking or selected tasks in restaurants.

If food is frequently added and removed from the cooker, however, as often occurs during restaurant service, natural convection may not be enough to maintain an even temperature. Modern water baths use PID or PID-like controllers, but some older models use analog bang-bang controllers, which are less accurate.

A BASIC BATH

A spacer prevents the bags from impeding convection and protects them from being scorched by the heating element, which typically is mounted underneath the water reservoir.

Two walls with insulation in between improve energy efficiency and evenness of heating. This design offers no way to alter the size of the bath, however.

A lid is important to reduce evaporation, which cools the water near the surface of the bath faster than natural convection can mix in hot water from the bottom, and thus leads to uneven cooking.

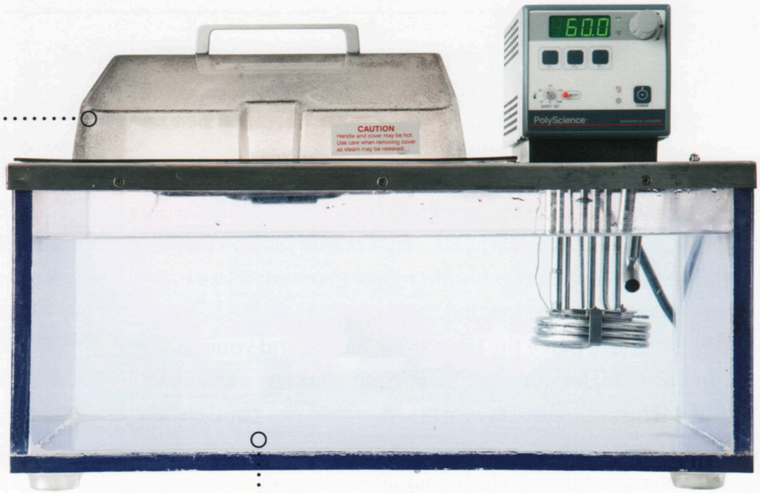
A wire rack helps separate bags of food so that natural convection can keep water circulating to moderate hot spots. Even with a rack in place, it is easy to overstuff the bath, so remember to leave room for currents.

When cooking with sous vide bags in a water bath, use a spacer to keep the bags from resting on the bottom of the bath. This step is particularly important in a noncirculating water bath, but it's always a good idea.

Laboratories often cover water baths by floating Ping-Pong balls on the water. The balls insulate the water from the air and slow evaporation and heat loss. The balls move aside easily when you move objects into or out of the bath.

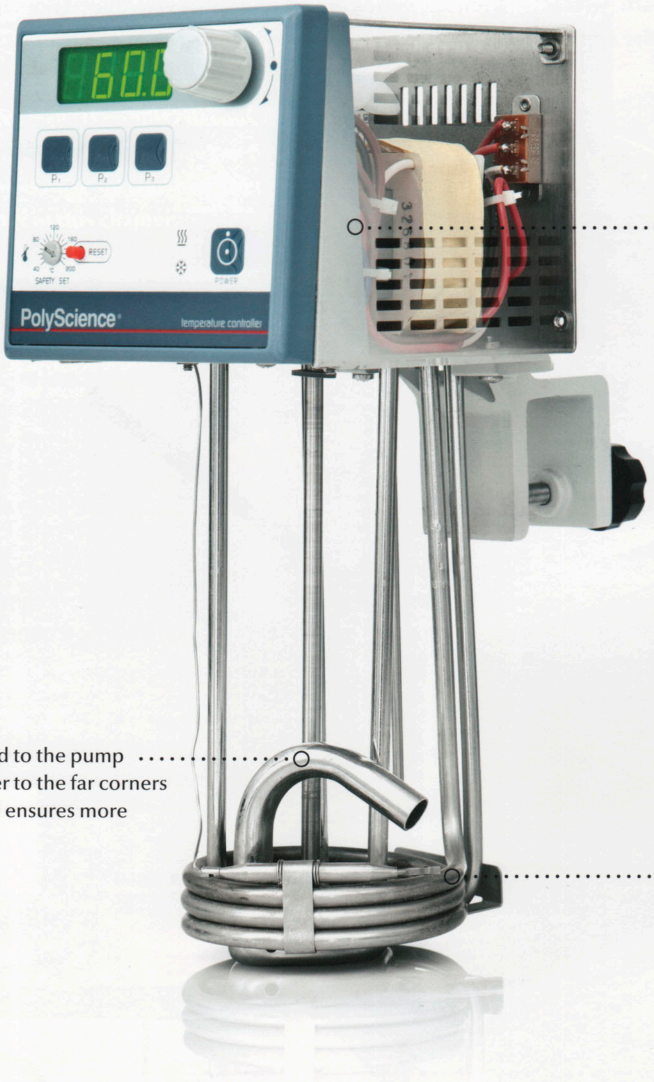
A CIRCULATING WATER BATH

A lid is even more important for a circulating bath than it is for a noncirculating bath. Evaporation from an uncovered bath can lower the water level so much that the heating element and pump motor sustain damage. And if enough water evaporates, bags of food will be left uncovered, which will create a food safety hazard.



A portable immersion circulator with digital controls can be used in baths of various sizes and designs.

Acrylic construction provides adequate insulation for smaller baths, but large baths should have insulated double walls to prevent hot and cold spots from forming. Avoid a single-walled metal container, such as a large pot, which virtually guarantees uneven heating. Instead, inexpensive plastic coolers can be adapted to do an excellent job.



Pumps agitate the water in circulating baths to give natural convection a boost. Pumps are more efficient and robust than propellers. Typically the agitator and a heating coil enter the reservoir from the top. That arrangement makes it easier to move the head unit from one bath to another. But this flexibility comes at a price: an immersion circulator usually costs more than a noncirculating bath of similar capacity. For a restaurant, the ability to maintain even temperatures, even as food is continually added and removed, easily justifies the extra cost.

A protective cage (optional, shown on page 229) protects the heating coil and circulation system. It also prevents the heating element from scorching sous vide packaging.

A tube attached to the pump drives hot water to the far corners of the bath and ensures more even heating.

The immersed heating element reduces the usable volume of the bath and requires more effort to clean than external heaters do.

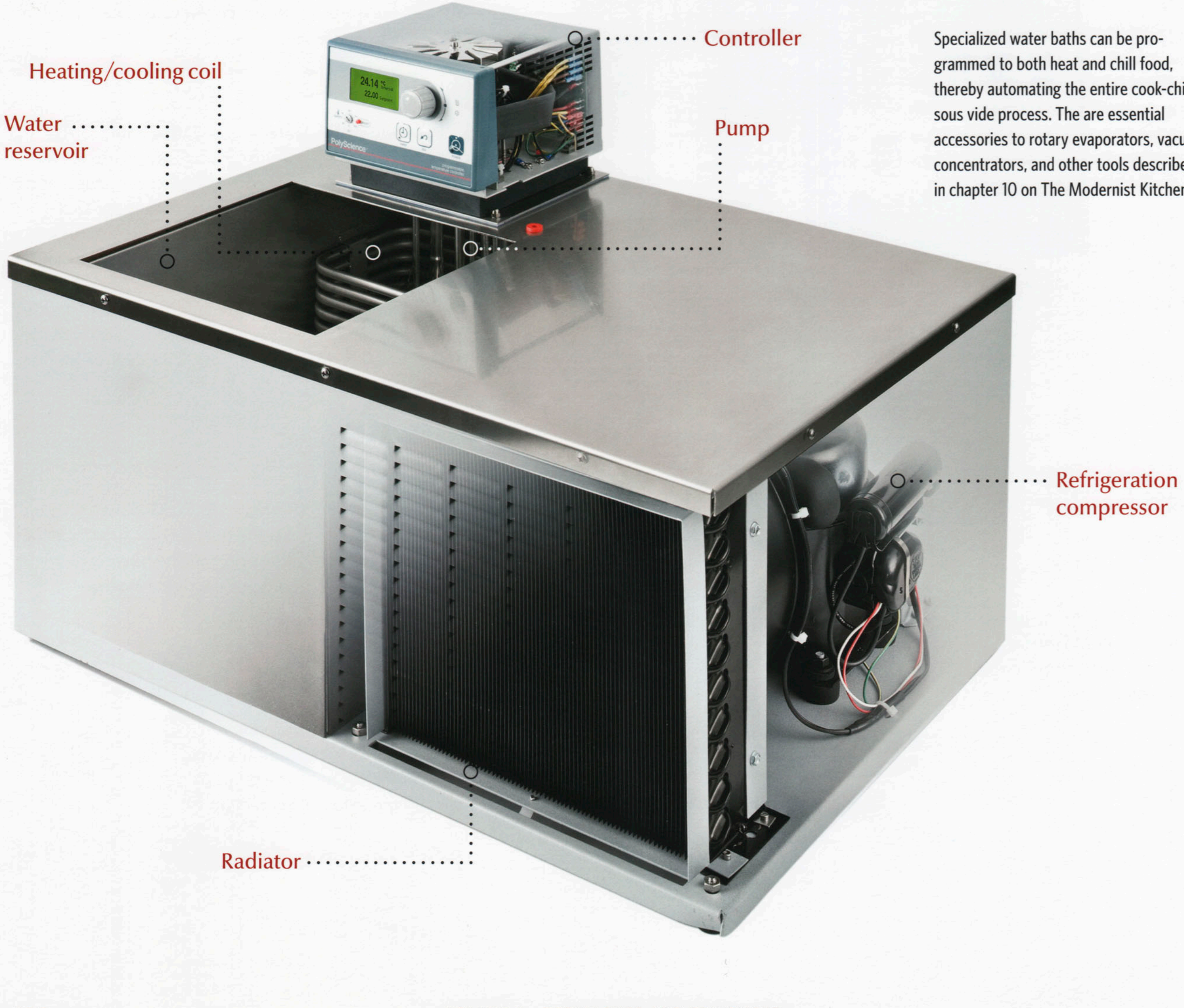
THE TECHNOLOGY OF

Chilling Water Baths

Some models of water bath are good not only at heating food but at chilling it, too. Chilling water baths come in two styles: immersion and reservoir. An immersion chiller works much like an immersion heater, except that the coil you plunge into the liquid gets cold rather than hot. If you have an immersion heater that has a data port on the back, you may be able to place the immersion heater and your immersion chiller in the same bath and connect them with a data cable. (This setup usually works only if the heater and chiller are the same brand.)

A reservoir chiller includes a built-in circulating water bath, heating system, and refrigeration system. Baths in these units are typically rather small, but some reservoir chillers include a duplex pump that can be used to add an external bath, which greatly expands the cooking or chilling capacity of the appliance. You can connect two hoses from the duplex pump to another water-filled container, such as a large plastic cooler. The chiller will then circulate both the water in its built-in bath and the water in the external tub through the heat exchanger to control its temperature.

Chilling water baths are expensive but invariably include a full-featured, programmable PID controller, so you can set up customized heating and cooling processes, such as a heating stage followed by a holding stage and later a cooling stage. This flexibility can be very handy when a very long-cooking sous vide recipe needs to be taken out of the bath and chilled in the wee hours of the morning! Programmable heating and cooling water baths can start and stop cooking automatically, then keep the cooked food properly chilled until the chefs return to work.



Specialized water baths can be programmed to both heat and chill food, thereby automating the entire cook-chill sous vide process. The are essential accessories to rotary evaporators, vacuum concentrators, and other tools described in chapter 10 on The Modernist Kitchen.

Other Ways of Cooking Sous Vide

Although water baths have become synonymous with sous vide cooking, other kinds of cooking equipment can work just as well—or even better in very large catering environments that overwhelm the limited capacity of water baths. If you have to cook or reheat large amounts of food, then a forced-convection steam oven, a water-vapor oven, or an autoclave may be a better option. We cover forced-convection and water-vapor ovens (also called combi ovens or cook-and-hold cabinets) in chapter 8 on Cooking in Modern Ovens, page 150. An autoclave works in many ways like a pressure cooker or pressure canner, except that instead of being filled with water, the appliance directly injects steam into a sealed chamber. The steam increases both the pressure and the temperature.

Autoclaves typically heat water to hotter temperatures than pressure cookers do, and sometimes to more than 140 °C / 285 °F—hot enough that aroma-generating Maillard reactions accelerate dramatically. Those temperatures can cause regular sous vide bags to fail. Instead use special plastic retort bags, which will not melt or leak when used to cook sous vide in a pressure cooker or autoclave. The ability to cook food sous vide in a way that allows unrefrigerated storage can be tremendously convenient, but it does raise special food safety considerations, which we discuss later in this chapter.

The large capacity of an autoclave allows many portions to be cooked at once with simple, automatic, and accurate control of the process.

Homemade and Improvised Water Baths

The price of combi ovens and laboratory-grade water baths erects a formidable barrier for many cooks interested in sous vide. Although this expensive equipment is the best choice for cooks and restaurants committed to the technique, it is not necessary for those on a tighter budget. A pot, a good thermometer, and patience are enough to cook sous vide.

One dead-simple approach is to clip a digital thermometer onto the side of a large pot full of water. Heat the water to the target temperature, carefully adjust the burner to a setting that maintains the temperature, and start cooking. It's not even necessary to vacuum pack the food. Filling jars with raw food or suspending food-filled plastic bags in the water works fine. Although the temperature is unlikely to be steady enough for many hours of unattended cooking, this setup will cook food acceptably for up to a couple of hours. Just don't expect perfection.

Cutting-edge gastronomes may swear by laboratory-style baths, but fundamentally they are little more than crock pots with better temperature controllers. With a little effort, you can create such a system yourself by using a budget crock pot or rice cooker, as long as it has a simple mechanical on–off or low–medium–high switch; avoid any that is programmable or has digital controls. Avoid ceramic cooking vessels, because their high mass makes them slow to heat and cool. A thin aluminum cooking pot responds faster to temperature changes and provides better thermal stability.

You will need a PID controller to upgrade your appliance. At least one company (Auber Instruments, www.auberins.com) makes one for just this purpose. Plug the PID controller into the wall outlet, plug your cooker into the PID controller, and switch the cooker on, then drop the attached temperature sensor into the cooking pot. When you set the temperature on the PID controller, it controls power to the cooker to maintain the target temperature. A system like this can be had for slightly more than $100 and is essentially equivalent to a noncirculating bath that costs substantially more.

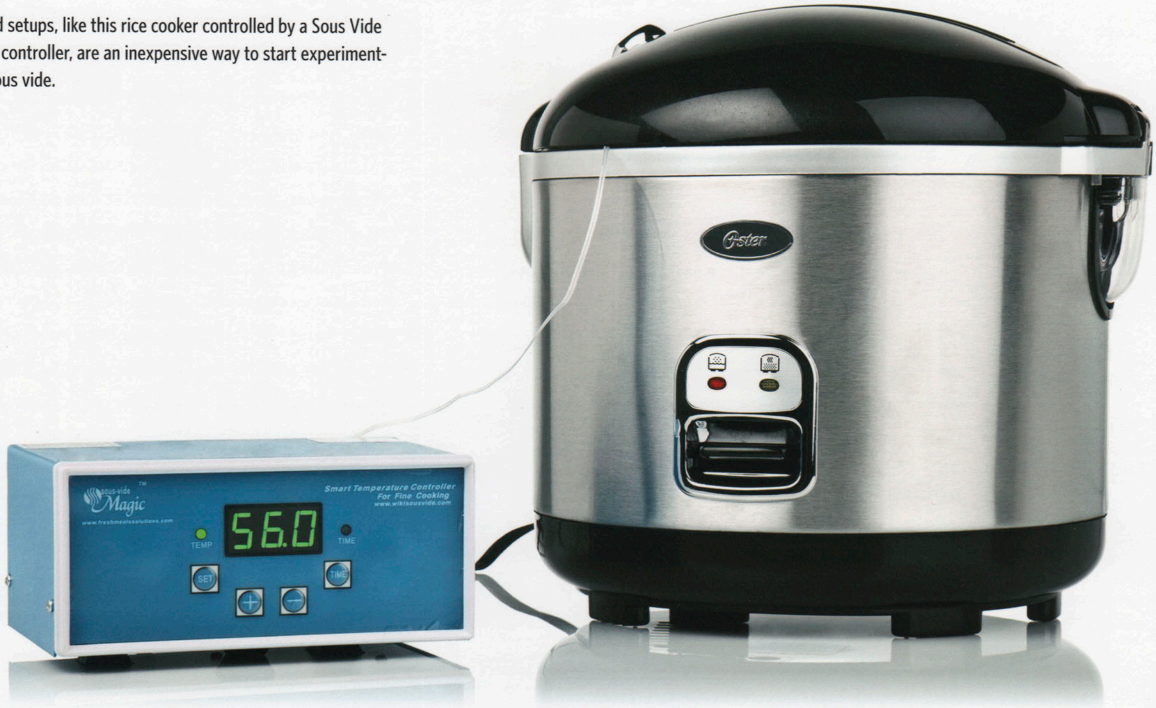
As is true of any noncirculating bath, these improvised systems may heat unevenly, particularly when overloaded with too much food or when food bags come too close together. A simple way to even out the heating is to add an inexpensive aquarium air pump and bubbler to the pot. The bubbles stir the water and help prevent cold spots from developing. Because the air being pumped in is at room temperature, the system

In the early 1980s, the Canadian scientist Pierre de Serres developed an improvised sous vide system for home cooks. De Serres's system included a "Smart Pot" that was essentially a slow cooker with a simple adjustable temperature controller. Although he promoted it tirelessly, the idea was ahead of its time. Today, an actual de Serres's "Freedom Cooking System" is a rare historical curiosity, but the spirit of his idea is inexpensively recreated and improved by plugging a simple rice cooker with a mechanical switch into an external temperature controller that adjusts the power delivered to the rice cooker to maintain a stable temperature.

For more on the historical development of sous vide cooking, see page 1·40.

Perhaps the simplest way to cook sous vide—although certainly not the most convenient or accurate—is with some zip-closure bags and a pot with a digital thermometer clipped to the side.

Improvised setups, like this rice cooker controlled by a Sous Vide Magic PID controller, are an inexpensive way to start experimenting with sous vide.



does tend to cool the water somewhat, which may make the heater work harder. But usually the loss of efficiency is worth the better circulation.

Clever cooks have improvised many other ways to cook sous vide without professional-level equipment. Ultimately all that is needed is a way to heat food accurately at low temperatures. An oven with the door cracked open can sometimes work, as can a sink filled with running hot water. Some cooks have had success with cooking pots designed to go into heavily insulated thermos bottles. Vacuum-sealed food is put into the pots, hot water is added, and then the whole arrangement is sealed inside a thermos until the food finishes cooking. Inside the thermos, the food heats up as it cooks, and the surrounding water cools down. Some trial and error is thus needed to figure out how much hotter than the target temperature to make the water so that it and the food eventually equilibrate to the perfect temperature. Nevertheless, this system provides a great opportunity to take sous vide out for a picnic at the park.

STRATEGIES FOR COOKING SOUS VIDE

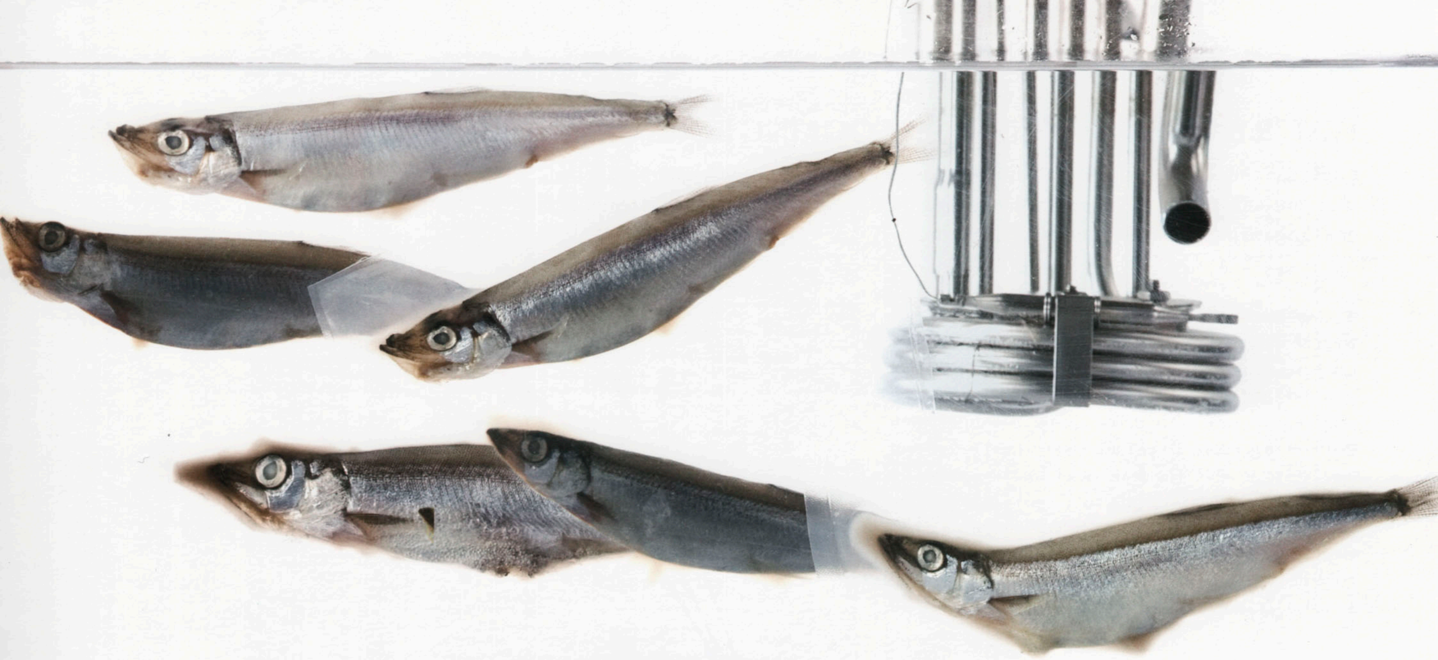
One of the most appealing features of sous vide cooking is the flexibility it offers cooks in dealing with a wide range of culinary situations, ranging from immediate service with minimal advance preparation to cooking directly from the frozen state. We have collected strategies for using sous vide in all the circumstances to which it applies and have divided them into two groups (see table below).

In most situations, the approach that will work best will be immediately clear. Sometimes, however, you may face a choice between the strategy that will produce the best-tasting, most attractive result and alternatives, such as freezing and later reheating, that are more convenient or economical. This section and the two that follow step methodically through the many possible ways to prepare and store food sous vide and offer tips and safety considerations for each. Once you understand the strengths and limitations of each strategy, you'll be well prepared to use sous vide appropriately in all the areas in which it excels.

Strategies for Sous Vide: A Comprehensive Guide

Professional chefs usually cook sous vide at low temperatures; when cooking times are long enough, low-temperature cooking can even pasteurize food for long-term refrigerated storage. Another type of cooking, involving cooling cooked food and heating it again, comes into play when food must be prepared well before it can be served. For long-term unrefrigerated storage, see Canning, page 75.

Cooking at Low Temperatures	
Cooking to a target temperature (page 243)	Remove the food for service as soon the core temperature hits the target, which may be a few degrees below the final desired temperature if you are using a bath that is hotter than the target temperature.
Holding at the target temperature (page 247)	Allow the food to reach its final core temperature, then hold it there—typically for 4–72 hours—to achieve the desired texture. This strategy is also useful for accelerating the aging or ripening of certain foods and for extracting or infusing flavors.
Holding until pasteurized (page 249)	Cook to temperature, then hold there until the the time-temperature combination is sufficient to reduce the levels of the most dangerous bacteria and parasites by 6.5 orders of magnitude (99.99997%). This procedure is done for food safety reasons. It is also required if you chill food and hold it for later use.
Chilling and Reheating Strategies	
Chilling (page 254)	Prepare foods for refrigeration by chilling them quickly. Once chilled, they may be held cold for a period of time for later use.
Freezing (page 256)	Freeze food quickly because the faster the food freezes, the better its texture when thawed. Cryogenic freezing is discussed on page 456.
Thawing or cooking from frozen (page 258)	Use a water bath to quickly and conveniently thaw frozen foods or cook them straight from the frozen state.
Reheating (page 262)	Warm foods that have been cooked hours or days in advance and chilled until needed for service.



Cooking Food to a Specific Temperature

The chemical reactions that transform food from raw to cooked can be very fast; once a critical temperature is reached, the food is essentially cooked, and it does not cook further with more cooking time. The simplest strategy for sous vide cooking is thus to heat the food until its center reaches the desired temperature, then immediately pull it out of the heat.

This approach works well for tender red meats, poultry, fish, and other seafood, as well as for some fruits and vegetables. But tough meats, many fruit and vegetable preparations, and most grains and legumes do not respond well to this treatment. The key chemical reactions responsible for the transformations we call "cooking" take time to happen in these foods. Another cooking operation that takes time is pasteurization—killing pathogens that may be present in the food. In most cases, cooking just to a given temperature is not enough to pasteurize food; the food must be held at a temperature for a specified time.

You can use either of two heating techniques to cook food to a specific temperature. The first is to set the bath slightly above the desired temperature. The second is to set the bath much hotter than the final target temperature.

USING A BATH SET JUST ABOVE THE TARGET CORE TEMPERATURE

The simplest (and in our opinion best) approach for sous vide cooking is to set the bath temperature one or two degrees above the desired target temperature. This approach is called **equilibrium cooking** because the food temperature comes into equilibrium with the bath temperature.

The advantage of this technique is that the food cannot overcook. This benefit is particularly important when you are cooking food that is irregularly shaped—the appropriate cooking time will be determined by the thickest parts, but the thin parts can't overcook.

Another advantage to this approach is that timing does not matter that much. The food takes time to reach the target temperature, but heating is very gradual during the last part of the cooking process. So if you take the food out of the bath a bit early or you leave it in the bath longer than the recommended time, nothing bad will happen.

The disadvantage to this approach is that the cooking is very slow. Heat transfer is proportional to the temperature difference between the food and the bath (see page 1·277). As the food temperature approaches the target temperature, the heat flow into the food steadily decreases. So cooking times increase, and that can be inconvenient.

With the exception of pressure cooking and low-temperature (below 60 °C / 140 °F) cooking applications, the sous vide strategies discussed here all work well in a water bath, water-vapor oven, combi oven, or some other setup. We refer to water baths simply for convenience.

For more on how to choose the target temperature that will produce the texture and tenderness you desire, see Cooking Meat and Seafood, page 3·70.

For more on why holding times are critical for pasteurization, see Bacterial Death, page 1·148.

WATER BATH STRATEGIES FOR COOKING SOUS VIDE

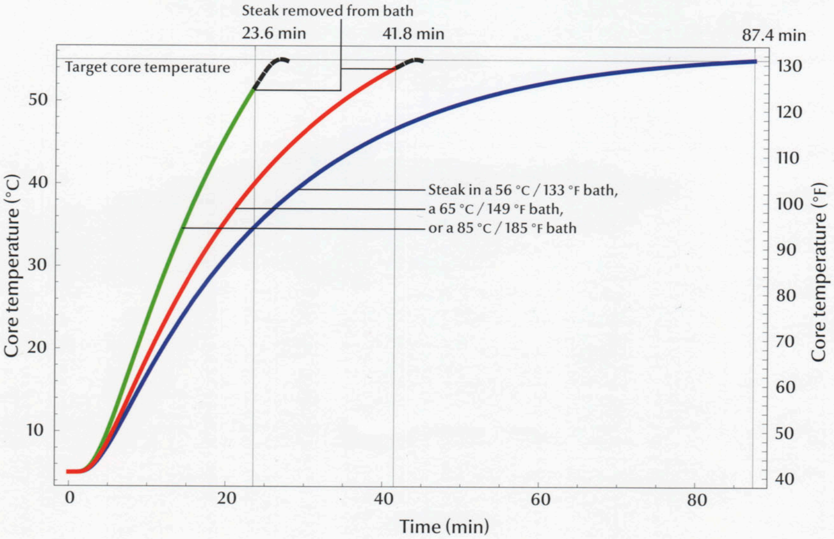
Cooks can choose among three main strategies when cooking sous vide: set the bath at the final core temperature you want to achieve, make the bath hotter than that target temperature, or use two or more baths at different temperatures.

Bath set just above final core temperature

You can use this approach in almost every situation—if you have enough time. It is simple and nearly foolproof: the food can't get hotter than the bath, so it can't overcook because the bath is set just one degree higher than the target core temperature you want the center of the food to achieve. The drawback is that because of the nature of heat transfer, the food can take a very long time to complete the final few degrees of cooking. The lengthy cooking period may not matter if you plan to hold the food at the final temperature for a long time in any case (as shown in the blue curve at right).

Bath hotter than target temperature

Setting the bath hotter than the desired final food temperature will shorten the cooking time dramatically (green and red curves). But in exchange for expediency, you will have a narrower window of opportunity during which the food can reach ideal doneness: remove it too soon, and it will be undercooked; take it out too late, and it will overcook. The higher the bath temperature, the more precise the timing must be. With perfect timing, the center of the food will be at the right temperature, but the exterior will be overcooked.



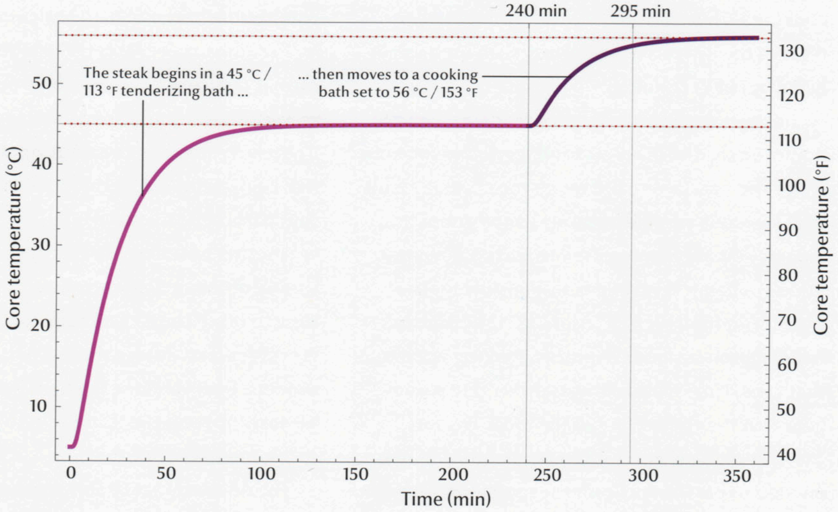
The speed at which the temperature rises at the center of a steak 30 mm / 1¼ in thick depends on the temperature of the cooking bath. In a bath set to 56 °C / 133 °F, the meat reaches the target temperature in about 87 min, and is close enough (0.7 °C / 1.2 °F) to the target by 77 min that it will not be undercooked (blue curve).

In a bath at 85 °C / 185 °F, the food must come out of the bath at a much more precise time (23½ min), then rest for almost 10 min as the core temperature drifts upward to the target (green curve). Although cooking takes only a third as long as in the previous case, the risk of overshoot is higher, and 40% of the steak will experience temperatures over 60 °C / 140 °F and will thus be medium rather than medium-rare.

Two or more baths at different temperatures

To use this combination strategy, use baths set to different temperatures. If the first bath is very hot, it can actually blanch the food and reduce any surface contamination to safe levels, but searing with a blow torch works even better.

A more complex setup starts with a torch searing, then uses a low-temperature bath to activate enzymes that tenderize the meat. You then move the food to a second bath to bring it to the final cooking temperature.



The core temperature of the steak rises in stages over the course of several hours when the steak is seared with a blowtorch, then placed in a tenderizing water bath followed by a cooking water bath. The graph shows the calculated temperature at the core if the steak sits in the first bath for 4 h—long enough to activate enzymes in the meat that help tenderize it—then cooks in a hotter bath to a final core temperature of 56 °C / 153 °F, which takes an additional 55 min. Leaving the steak in the cooking bath for 24–48 h will tenderize it further.

You might wonder why you can't just set the bath temperature to exactly the target temperature. The answer is that the food will never reach the target temperature; instead, it will remain slightly below it. In most cases, however, there is no practical difference between setting the temperature to target and setting it one to two degrees above target temperature because most food is not sensitive to that small a difference. Most kitchen thermometers can't sense more accurately than that. (Note that, because 1 °C is 1.8 °F, the recommendation works in either scale.)

As discussed in chapter 5 on Heat and Energy, the physics of heat transfer makes the cooking time proportional not to the thickness of the food but to approximately the thickness *squared*. So whereas a water bath set to the target temperature will cook a cutlet that is 5 mm / ¼ in thick in less than two minutes, a 150 mm / 6 in rib roast will have to sit in the same bath for 8½ hours until it is done! Cut the roast in half lengthwise (reducing the thickness), and it will cook in a quarter of that time. For this reason, we generally try to keep sous vide portions small.

Even professional cooks often lack an intuitive sense of this law of heat conduction because we typically cook small and thin pieces of food by pan-roasting, grilling, or stir-frying over high heat, whereas we use usually roast or braise large pieces in an oven. Conventional cooking does not give you a good intuition for how long food will take to cook sous vide.

USING A BATH SET HOTTER THAN THE TARGET CORE TEMPERATURE

Cooking with the bath set to the final temperature works so well that it begs the question: why would anyone use a hotter bath? Some chefs do prefer cooking this way, and frankly it can be hard to explain that choice.

Many people who advocate cooking with a bath hotter than the core temperature do so out of a misplaced concern about food safety. Some say that it is safer to cook with a water bath at 60 °C / 140 °F or even 63 °C / 145 °F, even if their desired final temperature is substantially lower than that. In general, however, a hotter bath actually makes little or no difference in the safety of the food, as explained in chapter 3 on Food Safety. In selected cases, scalding the exterior of food makes sense, but it is better to do this using multiple baths than to use a single bath that is too hot.

Some people choose to use a hotter bath because this approach can accelerate cooking. For example, a large roast that is 15 cm / 6 in. in both length and diameter will take approximately 7¼ hours to warm from 5 °C / 41 °F to a perfect edge-to-edge medium rare at 55 °C / 131 °F, if the bath is set just above the target temperature. When done, the outer edge of the roast will be the same temperature as the bath, and the center will be about 1 °C / 1.8 °F cooler, but its temperature will increase by about 0.5 °C / 0.9 °F after resting—a difference so minute that you could not detect it from the appearance, texture, or flavor.

If we instead set the water bath just 4 °C / 7 °F hotter, to 60 °C / 140 °F, then the time it takes the roast to reach 55 °C / 131 °F falls dramatically—from 7¼ to 4½ h. A bath 15 °C / 27 °F above the final core temperature will shorten the cooking time to just over 2½ h. In certain circumstances, the hotter-than-core approach can thus take sous vide from impractical to downright convenient.

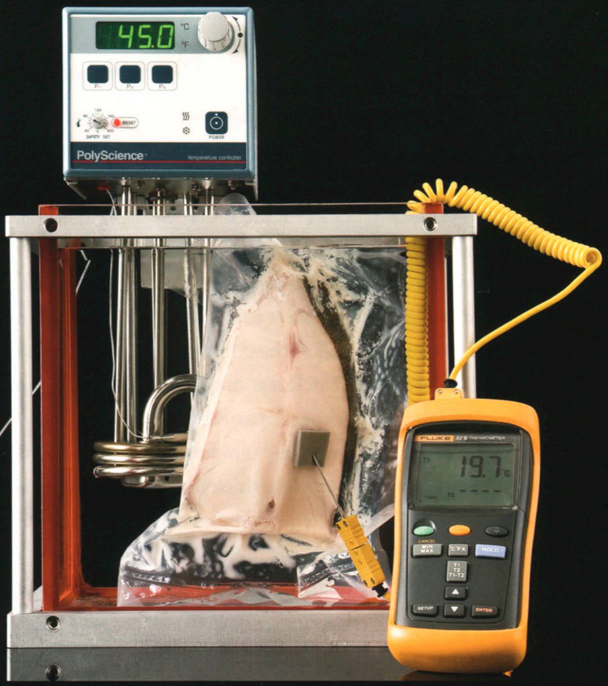
The acceleration comes at a cost, however. The farther the temperature of the bath rises over the desired core temperature, the more sous vide cooking is susceptible to the misjudgment of cooking time that plagues conventional high-heat cooking methods, and the steeper the temperature gradient within the food, which causes the outside and thinner parts of the food to overcook. A bath set 15 °C / 27 °F hotter than target may reduce the cooking time by almost a factor of three, but it also

HOW TO Cook in a Bath Set to Final Temperature

1 **Choose a target temperature.** Use experience, a recipe, or the tables on page 276 to select a desired final internal temperature for the food.

2 **Ready the bath.** Program the heater to maintain a temperature 1 °C / 2 °F higher than the target temperature, then wait for the bath to reach its set point.

3 **Cook until done.** Put the food in the bath, and cook either for a predetermined time (using tables or a recipe) or until a probe thermometer shows that the deepest part of the food has reached the target temperature.



HOW TO Cook in a Bath Set Hotter than Final Temperature

1 **Choose a target temperature.** Use experience or a recipe to select a desired final internal temperature for the core of the food.

2 **Ready the bath.** Set the temperature set point higher than the target temperature, and wait for the bath to reach its set point.

3 **Cook.** Put the food in the bath, and cook either for a predetermined time (determined by using tables or a recipe) or until a probe thermometer shows that the deepest part of the food is near the target temperature. It is difficult to judge the amount of temperature overshoot required. Once you do find the correct time, however, it will be repeatable as long as the food is identically sized, the cooking starts at the same temperature, and the bath is the same temperature.

4 **Rest the food.** The core temperature will continue to rise during resting by an amount that depends on the size and kind of the food. Once resting is complete, the food can be served or held in a second bath set to the target temperature.

Cooked to final bath temp

Bath set slightly hotter than core

Bath set much hotter than core

will heat much of the outside of a roast above 70 °C / 158 °F, turning it grayish white and depleting it of the juices that make it succulent.

Another problem is that it isn't easy to know when to remove the food from the bath. Heat keeps moving into the core during resting, so we need to take the food out of the bath well before the core reaches the desired final temperature or we risk overshooting the target. Too long in the bath, and we overdo it; too short, and the meal is underdone. In our opinion, the hotter-than-core method thus undermines one of the big advantages of cooking sous vide.

Using More than One Bath

Cooks who enjoy the luxury of having more than one water bath in the kitchen can take advantage of a hybrid approach that combines the accuracy of a bath set to the target temperature with a bit of the speed advantage of hotter-than-core cooking. You can set one bath to a scalding temperature—as hot as possible but typically at least 70 °C / 158 °F—and then set a second bath to the desired core temperature (or slightly higher).

Plunging the cold food into the scalding bath for 10 s–1 min alters the exterior of the food in several useful ways without overcooking the interior. The surface quickly pasteurizes, improving food safety. When cooking poultry or fish with the skin intact, a brief scalding can break down some of the connective tissue and render some of the fat from the skin, changes that can improve its palatability. Delicate meats, such as tenderloins, often benefit from a brief scalding because the high heat forces proteins on the surface of the meat to contract rapidly, which helps create a more attractive shape.

After blanching the food, you can transfer it to a separate bath set at, or slightly above, the desired core temperature to finish cooking it. For smaller portions of food, this approach can cut the cooking time by several minutes.

If a third bath is available, you can set it to a lower temperature—typically 50 °C / 122 °F—and use it in between the blanching and the cooking steps to tenderize meat. The intermediate bath will activate calpain and cathpepsin enzymes that break down contractile proteins in the meat. Because the tenderizing bath warms the food, less cooking time is needed in the third bath set at (or slightly above) the final temperature.

Holding Food at the Target Temperature

Cooks in a busy kitchen aren't always able to keep a close eye on a temperature probe to pull food from the bath the moment it reaches the target temperature. Coordinating the completion of a complex dish is easier if you can simply hold all the components at their final temperature until it is time to assemble them. Fortunately, most foods can sit at their target temperature for some time without harm.

Indeed, some foods improve from holding, which is effectively the Modernist version of braising. Like braising, holding meat sous vide can almost magically tenderize tough cuts into flaky and tender morsels—the culinary equivalent of making a silk purse from a sow's ear. The mechanism at work here is not magic, of course, but a chemical process known to scientists as **hydrolysis** or **denaturing**, which breaks down the collagen that holds the muscle together. Although no one would mistake the kind of tenderness that results from this process for the inherent tenderness of a medium-rare filet, it is still satisfying.

When cooking in a bath set well above the target core temperature of the food, use food that is as uniform in shape as possible. Otherwise, thinner parts of the food will overcook before the centers of the thickest parts are done.

Older cookbooks often say that during gelatinization, collagen turns to gelatin at some specific temperature. That is misleading: the reaction that transforms collagen to gelatin takes time. The amount of time depends on the cooking temperature. In addition, the life experience of the animal affects the structure of the collagen in its muscles, so the exact reaction time can vary from one piece of meat to the next.

Like most chemical reactions, collagen breakdown proceeds faster at higher temperatures. There is a tradeoff between speed, texture, and appearance, however. Traditional braising—in which the simmering liquid is typically at 80–88 °C / 176–190 °F—may take only a few hours, but it leaves the meat gray and somewhat dry as well. A sous vide approach can produce a better result, albeit far more slowly. Cook a tough cut of meat sous vide for 12–96 hours at 54–65 °C / 129–149 °F, and the meat is juicier than it would be if it were traditionally braised; its texture, color, and flavor are closer to those of a medium-rare filet.

For more on collagen and its role in cooking meat, see How Muscle Works, page 3·6, and Cooking Meat and Seafood, page 3·70.

Holding food at the final cooking temperature has several uses besides tenderizing, including aging meats and softening plant foods. The chemical and enzymatic reactions that produce the

pleasant aromas and tenderness of aged meat occur much more quickly in a hot bath than in a refrigerator (see Aging or Ripening Sous Vide, page 250). And one often needs to hold starchy vegetables, legumes, grains, and other food from plants in a bath for some time to allow water to penetrate the seed coat and soften the core. Classic dishes such as risotto only attain their thick, rich texture after a period of hydration that swells and extracts some of the starch from the rice grains. As with the breakdown of collagen, many variables influence the time needed to age and soften food sous vide so trial-and-error is often the best way to determine the holding time.

For more on the nuances of cooking plant foods, see chapter 12 on Plant Foods, page 3·258.

If you will be holding the food for a very long time—say 36 hours—don't worry about figuring out how long it will take the food to reach the target core temperature. Even if it takes a couple of hours to hit the target, that is still a small fraction of the cooking time. Typically, when the bath is set at or near the final core temperature, a variation of up to 10% in the holding time makes no noticeable difference in the quality of the food. Even if the holding time is a mere five minutes, pulling it out 30 seconds too early or too late shouldn't matter. And if the holding time is 36 hours, you can give yourself as much as four hours' leeway.

When cooking large items over long periods of time, it's generally not a good idea to set the bath hotter than the desired final food temperature unless you are using multiple baths. A multibath

HOW TO Cook in Multiple Baths

1 **Prepare a scalding bath.** Set the bath temperature as hot as possible but to at least 70 °C / 158 °F. Boiling water is fine for an initial scalding bath, and the food does not need to be scalded in a water bath–a pot of boiling water or a combi oven set to steam mode will also do.

2 **Ready the cooking bath.** Set the heater at or above the desired final core temperature for the food, and wait for the bath to reach its set point. See page 246 for details.

3 **Ready the tenderizing bath (optional).** If a third bath will be used, set the heat controller to 50 °C / 122 °F, and wait for the water to warm.

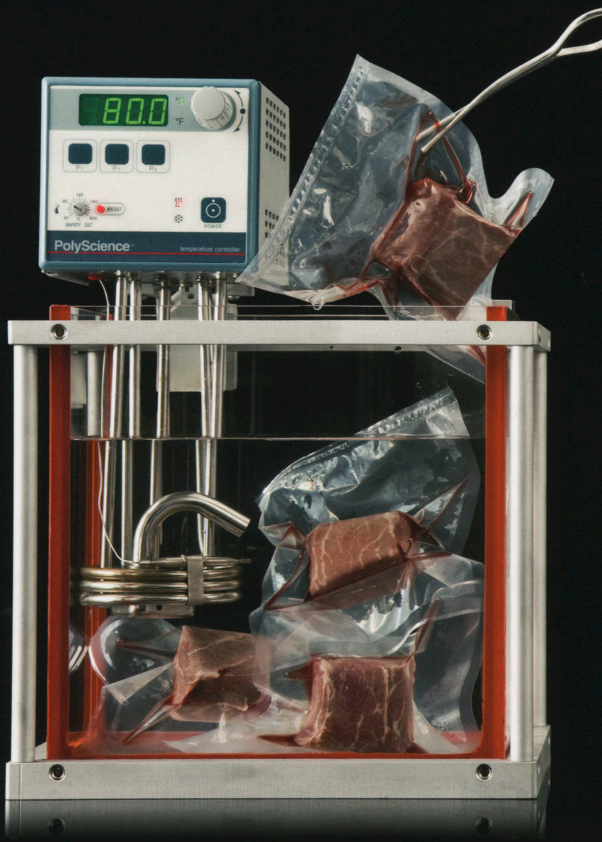
4 **Blanch the food.** Dip the food into the scalding bath for 10 s–1 min, depending on the bath temperature and the size and kind of food.

5 **Tenderize the food (optional).** Move the food into the tenderizing bath, if available, and hold for up to 4 h. (Tender meats do not need this step.)

6 **Cook the food.** Place the food into the cooking bath, and cook as desired. Follow with a resting period if needed.

7 **Hold until service (optional).** Once resting is complete, the food can be held in a bath set to the target temperature until it is needed for service. The scalding or tenderizing bath can be reset to final temperature and used for this purpose.

Scalding bath: at least 70 °C / 158 °F



approach can be the safest way to go if the food is so large that the core temperature will spend hours above 10 °C / 50 °F but below 54 °C / 130 °F. Because bacteria thrive in that temperature zone, it's important to reduce the surface contamination of the food as much as possible at the beginning.

The easiest way to do this is to blanch the food briefly before putting it into the primary cooking bath. (Note, however, that this approach doesn't solve the contamination problem for forced meats or food with punctures or fissures that admit bacteria deep inside.) Preblanching is imperative if you intend to tenderize the meat in a very low-temperature bath (below 54 °C / 130 °F), in which surface bacteria could proliferate quickly.

Pasteurizing For Storage

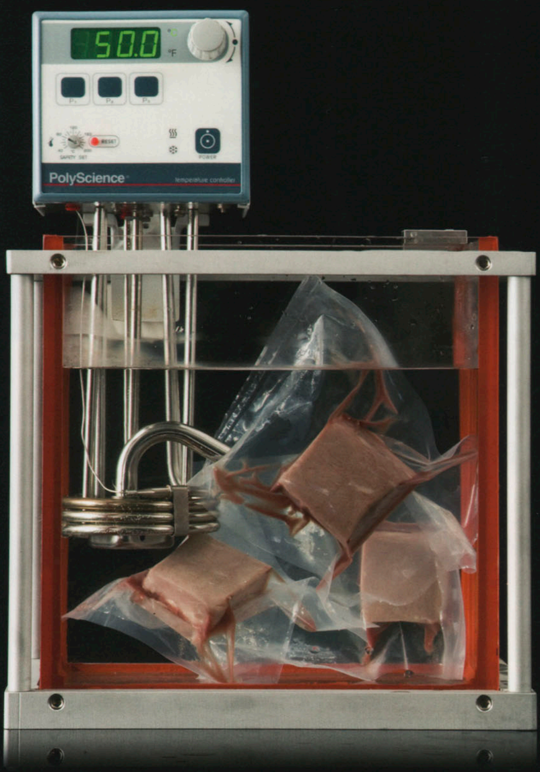
What does it mean to cook food until it is safe to eat? We address this complicated question in great detail elsewhere in this book. The science of microbiology is covered in chapter 2, for example, and chapter 3 provides a thorough discussion of food safety rules.

In part because the underlying biology is complex, the terms used to describe it can be confusing. Some people use sterilize to mean cooking that is sufficient to kill pathogens and render food safe to eat. Others use the terms sanitize or pasteurize in a similar sense.

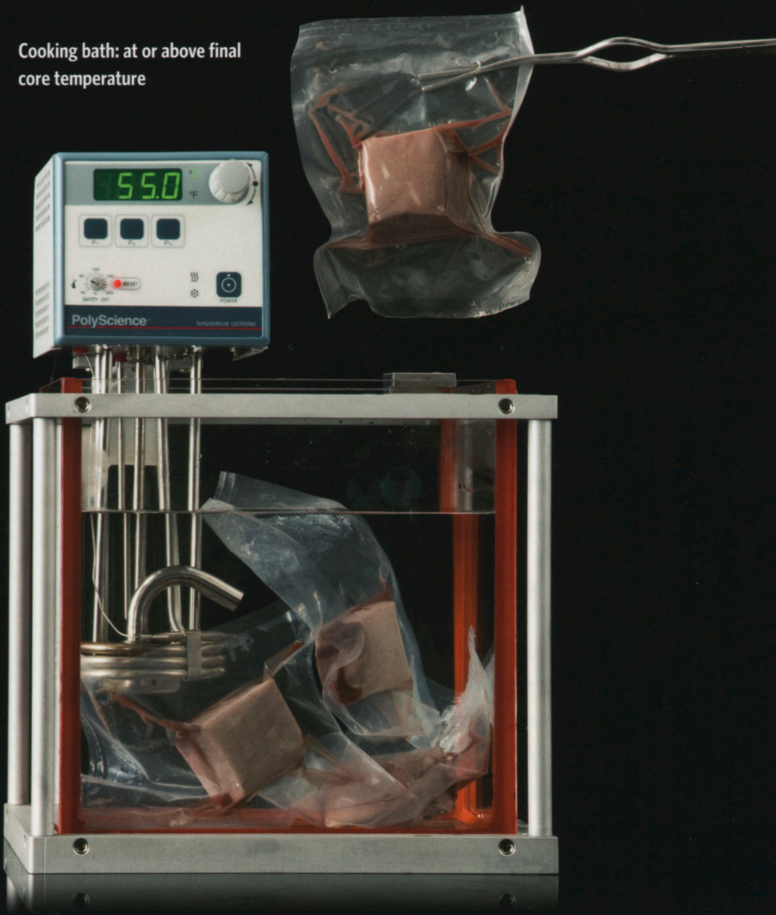
Technically, none of these terms is strictly accurate in describing what cooks do. Sterilization (as used in medicine) means killing or inactivating

When cooking tenderloin sous vide, you can obtain perfectly round medallions by rolling the meat tightly in plastic wrap before vacuum packing, then briefly dipping the bags in scalding water.

Tenderizing bath: 50 °C / 122 °F



Cooking bath: at or above final core temperature



essentially every pathogen, including the heat-resistant spores and toxins produced by certain anaerobic bacteria. Truly sterilizing food requires lengthy cooking in a pressure cooker or autoclave. That may be fine (even necessary) for canning, but it is literally overkill if the food will be served immediately or chilled soon after cooking.

Sanitization and pasteurization are not as well defined. Both terms are used to describe treatments that disable some but not all dangerous microbes and that may or may not destroy toxins. Pasteurization is familiar because of its wide use to improve the safety and shelf life of dairy products, fruit juices, and even beer. Dairy pasteurization involves very specific processes that require temperatures and holding times that differ from those required for most other foods. Nevertheless, most cooks and cookbooks refer to pasteurization when talking about safe cooking, so we will, too.

Let us be clear what we mean when we refer to **pasteurization**, however. We mean cooking food to an extent that meets a common standard set by regulatory agencies to reduce the risk of foodborne illness to an acceptable level. That means supplying enough heat for enough time to reduce the population of pathogens by 99.99997%, or 6.5 orders of magnitude. In the scientific literature, microbiologists refer to this as a 6.5D process. In food "cooked to 6.5D," for every three million microbes (of a particular strain) active in the food before cooking, only one microbe remains viable after cooking.

Sous vide methods make it relatively easy to pasteurize food to this standard. Bag the food, bring it to a specified core temperature, and hold it there for a specified time (see the tables in chapter 3). Pasteurizing sous vide, in other words, is simply cooking and holding food at a target temperature, except that the time is selected not for optimum texture but rather for sufficient food safety.

Pasteurization is required for two reasons. One is to ensure intrinsic food safety. Many foods, like poultry, have a history of pathogen contamination, so health authorities recommend that they always be cooked to pasteurization levels. For other foods, pasteurization is generally considered optional, unless the food is being served to people who are elderly, ill, or have compromised immune systems.

Pasteurization is also required if the food will be stored after sous vide cooking and later reheated and consumed. This is sometimes called cook-chill sous vide. Food safety regulations require that food cooked sous vide be cooked to pasteurization levels. It can then be stored for up to 30 days at 1 °C / 34 °F and for up to three days at 5 °C / 41 °F.

Canning, which allows food to be stored at room temperature, requires a much higher level of pathogen destruction—a 12D process—discussed in chapter 7 on page 75.

The term pasteurization originated with Louis Pasteur, a French microbiologist who championed the germ theory of disease and in the 1860s invented a heat treatment that extended the shelf life of milk, vinegar, and wine (see page 84).

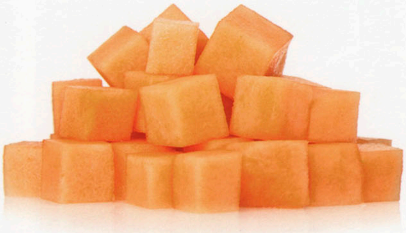
For more on pasteurization, sterilization, and how they apply to sous vide cooking, see chapter 3 on Food Safety, page 1·162.

THE TECHNIQUE OF
Aging or Ripening Sous Vide

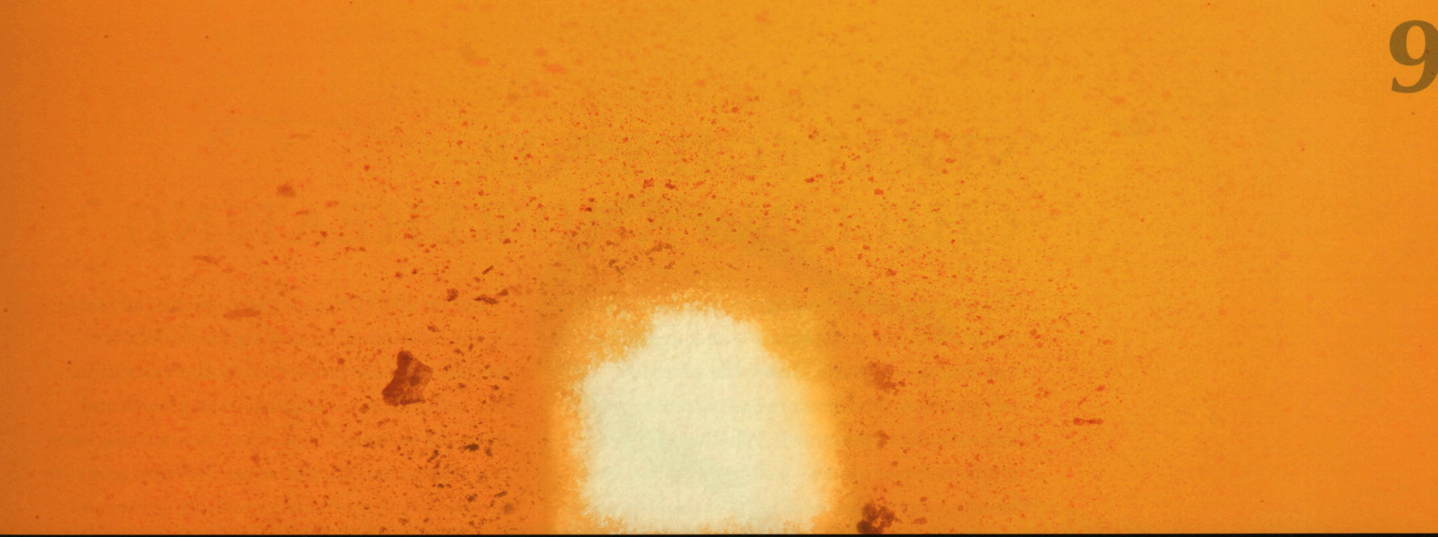
Fruits and vegetables ripen as a result of natural enzymatic reactions that accelerate at warmer temperatures. The aging process in meat works similarly. A warm water bath, set a bit cooler than the cooking temperature, thus offers a convenient way to age or ripen foods faster than normal.

We typically use temperatures near 38 °C / 100 °F for accelerated ripening or aging of plant foods. Higher temperatures tend to cook the food. For meats, aging is preceded by a quick blanching to reduce surface contamination.

This technique works for many fruits, vegetables, and meats—but not all. Melons ripen nicely in a sous vide bath, for example, whereas bad things happen to avocados.



For more on which fruits and vegetables ripen well in a sous vide bath and which suffer heat damage, see Cooking Sous Vide in chapter 12 on Plant Foods, page 3·286. For more on accelerated aging of meats, see Aging, page 3·39.



THE TECHNIQUE OF

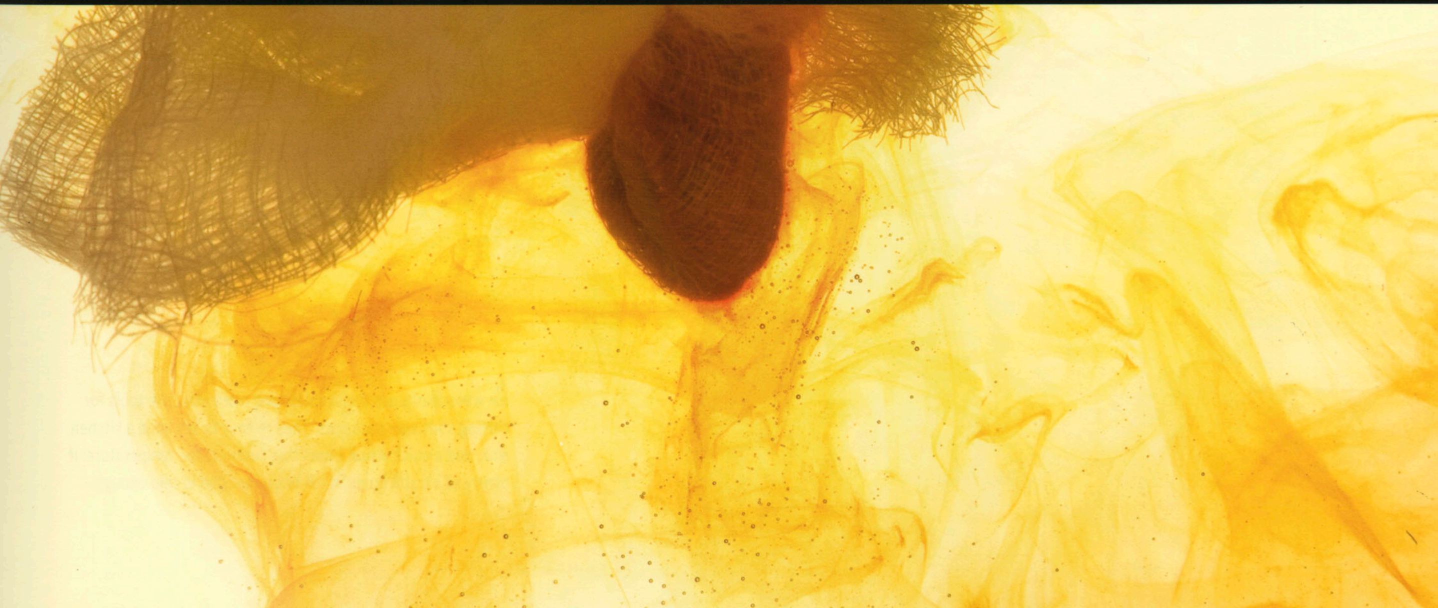
Extracting and Infusing Flavors with Sous Vide Cooking

Sous vide techniques offer a convenient way to pull liquids out of solid food (extraction) or, conversely, to encourage flavorful liquids to diffuse into the food (infusion). Much like tea, which can be made quickly by steeping tea leaves in hot water for a few minutes or slowly by steeping them in cold water for hours, sous vide extraction can be done at a range of temperatures.

Long, cool extractions or infusions can raise issues of food safety, so it is important to understand how susceptible the packaged food is to bacterial growth. If the extracting liquid is very acidic (having a pH below 4.6), or is very sweet (having a sugar content above 72 °Brix), or is very salty or high in alcohol content (containing more than 20% salt or alcohol by weight), it will suppress bacterial reproduction so much that extraction or infusion can be done safely at any temperature. The same is true if the food is too dry to support a large population of microbes: tea and coffee are cases in point.

When performing a lengthy infusion with fruits, meats, or other foods that can spoil, you have several options to maintain safety. One approach is simply to keep the food cold. That technique slows bacterial growth; it also slows the transfer of flavor, however. Health authorities generally consider any treatment safe if it takes no more than four hours (see chapter 3 on Food Safety). Longer holding times should follow the guidelines for time and temperature given in Pasteurizing for Storage on page 249.

Alternatively, use a pressure cooker or autoclave to extract flavors at high temperatures. This approach works faster, extracts flavors more completely, and (when guidelines for canning are followed) enables long-term storage of food without refrigeration. Ultrasonic baths are also excellent for flavor extraction (see page 302).



STRATEGIES FOR CHILLING AND REHEATING

Ironically, the sous vide technology that has revolutionized high-end restaurants was originally developed by the Swedish healthcare system to improve the quality of mass-produced hospital food—see page 1·40.

The invention of technology to chill food arguably made the modern restaurant—and, in particular, fine dining—possible. Before the advent of refrigeration, food vendors had to transform food dramatically to preserve it. Whether they used prehistoric techniques—salting, pickling, fermenting, drying, or smoking—or the Napoleonic-era innovation of canning, vendors had to invest substantial effort to create inventories of food that would stay palatable for days to weeks. Those treatments both added cost and limited the spectrum of possible flavors because, although the preserved food might taste delicious, it rarely tasted fresh.

Refrigeration and freezing allowed restaurateurs, caterers, and home cooks to vastly improve the quality of their dishes while simultaneously lowering the costs of producing them. With chilling, even ingredients procured and prepared well in advance can retain their fresh textures and flavors. Thus, large quantities of food can be held in a raw or partly prepared state so more customers can be served at each mealtime. Chilling also allows restaurateurs to recover unsold food and sell it another day, a capability that reduces waste and expands menu options.

But for all its culinary and economic advantages, the technology for cooling food does not entirely solve the problem of food preservation. Yes, refrigeration retards bacterial growth and slows the enzymatic and other chemical reactions that change food for the worse. Freezing goes even further: it halts bacterial growth altogether and prevents reactions among waterborne components of food. Neither process fully halts the oxidation of lipids and other fatty substances that eventually turns food rancid, however. Oxidated flavors are the telltale signs of poor ingredients and reheated foods. Sealing food in tight-lidded containers or plastic wrap slows rancidity only a little.

Sous vide techniques maintain the fresh-cooked flavor of food by eliminating nearly all oxygen from the cooking and storage environments. The cook–chill–reheat process lets even the most fastidious cook prepare a large variety of foods in advance and later warm them to order without compromising on quality. Small wonder, then, that cooking sous vide has been embraced in contemporary temples of gastronomy. It not only improves food quality and the bottom line, but it also frees professional cooks to attend to all of the other details of great cooking and service.

Ice water baths are the simplest and most effective tools for chilling sous vide packages. They're easy to set up in a kitchen sink, and a quick visual inspection confirms the temperature: if plenty of ice still floats in the bath, the food is cold enough.

Chilling

Skilled cooking is in part about controlling how heat is delivered to food. Chilling, on the other hand, is about *removing* heat, and it's usually given short shrift. That's unfortunate: skilled chilling is just as important to both the safety and the quality of food as is skilled heating.

For foods that will be reheated, proper chilling most often means rapid chilling. Cooked food should be cooled quickly for two reasons. First, bacteria grow and thrive in the "danger zone" from 10–50 °C / 50–122 °F (see page 1·175). The more time food spends in the danger zone during cooling, the more likely it is that the few bacteria remaining in it after cooking will multiply and dangerously repopulate the food. Most of the danger arises at the higher end of the range because bacteria multiply faster in a warm environment than in a cool one (see page 1·142).

Second, rapid cooling maintains juiciness and a fresh-cooked flavor better than slow cooling can. A quick chill thickens and gels juices before they

Conventional wisdom has it that slow resting provides time for cooked foods to relax and absorb juices that were squeezed towards the center of the food by the extreme temperatures of cooking. That assertion is incorrect, however. For a complete description of the surprising truth about resting—and why faster cooling leaves food juicier—see page 3·84.

THE PHYSICS OF

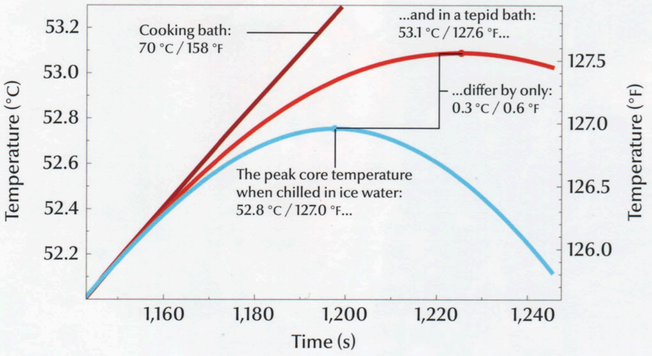
Why Cold-Shocking Doesn't Halt Cooking

A standard cookbook instruction is "plunge the food into ice water to stop the cooking." Unfortunately, the cooking doesn't stop when you do that. If you plunge food into ice water, the maximum temperature at the core will reach virtually the same temperature that it would if you plunged it into water at any temperature lower than the cooking temperature. Cold shocking doesn't work the way people think it does.

Suppose you are cooking food in a water bath (or by any other means), and you then plunge the food into ice water. The cold ice water draws heat from the hot food, but it takes time for heat to be transferred by conduction from the core. It also takes time, however, for heat that was put into the food a moment before the ice water plunge to conduct into the core. The conduction of heat inward and outward happen at the same speed (governed by the thermal diffusivity of the food; see page 1·277). So the temperature at the core reaches its peak when the last unit of heat from the surface reaches the core. At some point after that, the heat flow reverses, and heat starts to flow back out. But by that time, the maximum temperature has already been reached.

Computer simulations and physical experiments bear this out. The graph below shows the results of a computer model of the cooking of a thick steak in a 70 °C / 158 °F water bath (blue line). If we take the steak out after 18 minutes, the core will be at 51 °C / 124 °F. We could then put the steak in a tepid water bath at 30 °C / 86 °F or in an ice water bath at 1 °C / 34 °F. In both cases, the core temperature continues to drift upward as the meat rests, then peaks and declines as the meat cools. The meat in the tepid resting bath reaches essentially the same final temperature as does the meat in the ice-water bath. Cold-shocking makes only a tiny difference to the maximum temperature: less than 0.5 °C / 1 °F for a thick steak; for a thin steak, the difference is about 1 °C / 2 °F.

The ice water certainly cools the meat down faster after the peak temperature is reached, so it is a much better cooling option than the warm water bath. But it doesn't "stop the cooking"—it makes only an insignificant difference in the maximum core temperature.



We used thermal modeling software to calculate the peak temperature that the core of a steak reaches when it is plunged into either an ice bath (blue curve) at 1 °C / 34 °F or a tepid bath (orange curve) at 30 °C / 86 °F, after cooking in a water bath set to 70 °C / 158 °F (red line). The difference is negligible: a mere fraction of a degree. Cold-shocking does not prevent the core temperature of the steak from continuing to rise after it is removed from the heat.

The results shown at left reflect calculations made for a steak 2.5 cm / 1 in thick, but we also ran the simulation for thin steaks and found that the difference in core temperature is similarly tiny.

STRATEGIES FOR COOLING

Chilling equipment ranges from the inexpensive—yet surprisingly effective—tub of ice water to higher-tech, pricier options such as a blast chiller. More expensive technologies do not necessarily provide faster cooling, however—and often the opposite is true. Expensive chillers may provide greater convenience and additional control, but the speed of cooling is nearly always limited by conduction through the food itself, rather than by how quickly a chilling technology can draw the heat away.

Strategy	Cost	Pros	Cons
refrigerator	inexpensive	simple comes in large sizes	very slow insertion of hot food can warm food already inside
blast chiller	expensive	high capacity programmable circulating air accelerates cooling	expensive single purpose appliance that takes up space but is used only for cooling
ice-water bath	very inexpensive	simple very effective cools as fast, as or faster than, all other technologies ice provides a visual check that temperature remains safe	cools slowly and unevenly when overcrowded ice must be replenished
programmable heating/chilling bath	expensive	heats as well as cools cools quickly supports unattended cooking and cooling	limited capacity

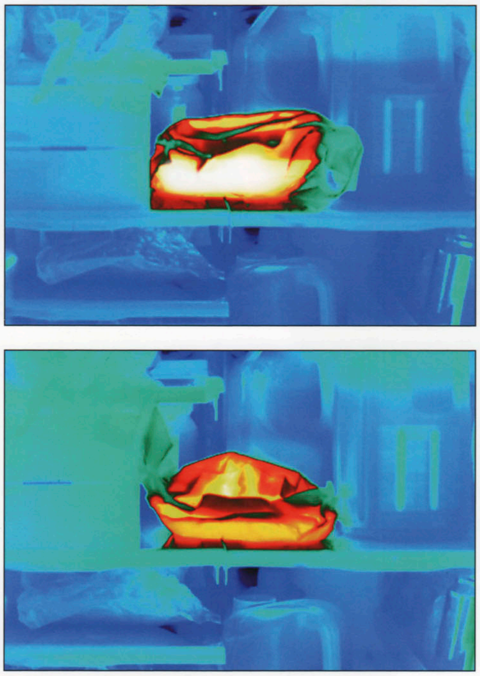
can leak out, and it keeps more of the aromatic volatiles that impart flavor where they belong: in the food rather than in the air.

The best way to quickly cool food to refrigeration temperatures is to dunk your sous vide bags in an ice-water bath, which can be as simple as a sink full of cold water and lots of ice cubes. As long as it's stirred occasionally, the ice water pulls heat away from the surface of the food evenly and with remarkable speed. As long as the bath is not overcrowded and a reasonable amount of ice is left, you know the water remains cold enough.

Food can be too small, as well as too large, for cook-chill sous vide. The juice in small food is never far from the surface and can easily leak during cooking. The optimum portion size is small enough to cook and cool quickly, but not so small that juices within the core can easily escape through the surface.

Whether you use an ice bath or a blast chiller, keep in mind that quick chilling will not completely halt cooking anywhere beneath the surface of the food. It's a common practice to "shock" cooked food in ice water, and many cooks seem to think it works because the frigid temperature of the ice bath stops the heat of cooking in its tracks. The laws of heat transfer say otherwise. (See Why Cold-Shocking Doesn't Halt Cooking, page 254.)

One of the primary concerns about cooling is that it takes time for large pieces of food to cool. Sous vide time and temperature combinations work for heating as well as cooling, so they can be used to estimate the time. Indeed, a basic rule of thumb is that it takes just about as long to cool a piece of food from cooking temperature to refrigerator temperature as it takes to cook refrigerated food in the first place. A roast that takes hours to cook is also going to take hours to cool. This time requirement is an important food safety consideration because pathogens can grow during the cool-down cycle.



As these infrared images reveal, the worst way to cool hot food is to place it straight into a refrigerator (top). Even after an hour (bottom), the package will remain quite warm. Meanwhile, this small package has slightly heated everything else in the refrigerator (lighter blue background), thus raising the risk of spoilage. If you have no other way to cool your cooked food, leave it on the counter until the heat dissipates somewhat so that it has a less dramatic impact on the air temperature when it goes inside the refrigerator.

Safety aside, you may want to avoid cooking and cooling a large, intact cut of meat sous vide simply because it's inconvenient. Better to butcher the meat into smaller, serving-size cuts, which will cook and cool faster. If you must chill and reheat a large intact piece—whether of meat or some other kind of food—place it after cooking in a bath set to the final core temperature, and hold it for slightly longer than you would for immediate service. The extra holding time improves pasteurization and safety. Finally, cool it rapidly to keep the food as juicy as possible.

Freezing

Although freezing food greatly extends its shelf life, it sometimes comes at a steep cost in quality. Frozen food can suffer a variety of insults as it languishes at subzero temperatures. The growth of ice crystals can damage its texture and drain it of juices. Flavorful aromatic compounds continue to evaporate and escape food that is frozen. And chemical reactions with oxygen slowly turn lipids and other fats in food rancid.

Vacuum packing circumvents many of these processes and thus makes freezing less problematic. The sealed bag acts like a second skin to halt evaporation of juices and volatile flavor compounds. By excluding oxygen, the packaging helps to prevent warmed-over flavors from developing during storage and reheating.

Ice crystals grow in frozen food regardless of how it is packaged, unfortunately. The problem plagues all frozen foods, whether raw, prepared by using traditional cooking methods, or cooked sous vide. Researchers have learned that it isn't the transition from fresh to frozen that does most of the damage to food. Rather, it is the slow and steady growth of ice crystals in the spaces between cells, a phenomenon that continues during frozen storage, that harms the texture and taste of frozen food (see page 1·304).

If you take precautions when freezing food and storing it frozen, however, you can thwart crystal

THE IMPORTANCE OF

Proper Refrigeration

Studies have shown that the average temperature of both domestic and commercial refrigerators often reaches 11 °C / 52 °F—far warmer than the recommended 2 °C / 36 °F. Refrigerator temperatures soar even higher if the door is in frequent use. Open the door on a typical domestic refrigerator, and an hour or more easily passes before the temperature inside returns to its set point. Compounding the problem are the hot and cold spots that exist in most refrigerators. Temperatures on the top shelves are often several degrees higher than those on the bottom shelves, and shelves built into the door are even warmer than the bottom shelves.

All of this is worrisome because proper refrigeration is crucial to the safety and quality of food. The low temperatures not only slow the growth of spoilage- and illness-causing bacteria but also retard chemical reactions that create off-flavors.

Refrigeration is especially important for vacuum-sealed food, which is vulnerable to deadly anaerobic microbes that can grow at just a few degrees above freezing. *Clostridium botulinum* and *Listeria monocytogenes* are among the worst of these oxygen-hating offenders. To keep them at bay as long as possible, hold your bags of sous-vide-cooked food just above 0 °C / 32 °F (see table at top right).

To ensure proper storage, use a good digital thermometer to find the hot spots and the cold spots in your refrigerator. Adjust the temperature setting to keep the hottest spot at no more than 5 °C / 41 °F. Store vacuum-packed food in the enclosed drawers at the bottom of the fridge, which maintain the most stable temperatures because they're protected from the thermal vicissitudes caused by opening the door.

Never store vacuum-sealed bags on door shelves, which are the hottest part of a refrigerator. Recheck the temperatures in your refrigerator regularly, and don't pack too much in it because overcrowding can heat up the contents.

Refrigerated Shelf-life for Pasteurized, Vacuum-packed Foods

Holding temperature		Maximum holding time
(°C)	(°F)	(days)
below −20	below −4	indefinite
1	34	30
5	41	3

growth and preserve more of the fresh food quality. Colder is better. Food in your freezer at −20 °C / −4 °F may seem to be frozen solid, but there is still a surprising amount of liquid water inside the food. This last bit of water won't freeze because its freezing point has been depressed below the temperature of your freezer by the proteins, sugars, salts, and other small molecules that make up food. Over time, this liquid water allows ice crystals to migrate and grow, which is what does the real damage.

Special cryogenic freezers used in laboratories, which operate at temperatures as low as −80 °C / −112 °F (or even colder), can almost completely stop the growth of damaging ice crystals. These freezers are ideal for long-term frozen storage. Temperatures this low supercool the last bit of unfrozen water within cells to a glassy state,

Just as it's inadvisable to chill hot food in a refrigerator, it's also a bad idea to put hot food into a freezer. The food will freeze too slowly and will thaw parts of neighboring foods. Always chill hot food to refrigerator temperatures or use a separate freezing strategy before putting the food in a conventional freezer.

Ice crystals grow on the surface of all frozen foods that undergo prolonged storage. Sealing food in a sous vide bag prevents water vapor in air from freezing onto the food's cold surface. But the bag will not stop crystals from slowly growing inside the food.

Ultra low temperature freezers that keep food at −238 °C to −150 °C / −60 °F to −76 °F are well worth the cost if you keep expensive foods for long periods of time. They can often be bought secondhand from laboratory equipment dealers.

For more on freezing with liquid nitrogen, see page 456. For more on frozen foie gras, see page 3·138.

eliminating all traces of liquid from the food. Few of us are able to store our frozen food in a laboratory-grade cryogenic freezer, of course. The next best thing is to keep the temperature in whatever freezer you do have as cold and stable as possible. Chest-style freezers are preferred to door-style freezers because chests are better at keeping the temperature constant.

Remember that each time a freezer door is opened, the cold air spills out, and the temperature spikes up. Moreover, freezers with automatic defrost cycles should not be used for long-term storage. After all, by design the defrost cycle warms the freezer enough to let built-up ice thaw! Defrosting—or anything else that allows the temperature of the freezer to fluctuate—allows ice crystals, especially those near the surface of the food, to resume their growth.

Colder is also better when freezing because quick freezing creates small crystals of uniform size. Ice in this form is less likely to damage surrounding tissue, either initially as it forms or later, during storage, as the crystals migrate and grow. Vacuum-packed foods have an advantage here as well because they can be frozen in a salt brine, a fast and effective method.

The salt in brine lowers the freezing point of water. Add enough ice to very salty brine, and it becomes cold enough to freeze most of the water in the food—as anyone who has used an old-fashioned ice cream maker knows. Ice floating in brine at 23% salinity will reach the lowest possible temperature of −21 °C / −6 °F. Liquid water is a good thermal conductor, so it sucks the heat from the food quickly and evenly. Brine freezing works so well that it's unfortunate that the approach is suitable only for food that has been vacuum-sealed in waterproof packaging.

Liquid nitrogen, at an amazingly low −196 °C / −320 °F (which is a mere 77 °C / 139 °F above absolute zero), freezes food colder and faster than salt brine does. But a cook who overzealously plunges food into liquid nitrogen to freeze it as fast as possible will find that the food suffers as a result. The outside freezes instantly. The inside freezes slowly, however, and expands as it does, so the surface of the food tends to crack and split. Liquid nitrogen is thus a good choice only for food that is small or thin enough that it can freeze inside and out at nearly the same speed.

The ultralow temperature and fast rate of freezing with liquid nitrogen causes other problems. We don't recommend it for meats and seafood, because the fast freezing irreversibly damages the proteins in a way that makes for a less juicy result when the meat is reheated. We also do not recommend freezing vacuum-packed foods in liquid nitrogen. The plastic packaging becomes brittle and tends to crack, which compromises both the safety and the quality of the food.

When to Thaw and When to Cook Directly from Frozen

It is so easy to warm a sous vide package of previously frozen food that one naturally wonders: is it better to thaw the food before cooking, or can you move it straight from the freezer to a water bath—and thus do the thawing and cooking in one swift step? The answer is that either approach works, and each has certain advantages.

In most cases, you'll want to take food directly from the freezer and put it into a water bath to cook it. Some foods, such as foie gras, are best when quickly frozen immediately after slaughter, then stored deeply frozen. These should be portioned frozen, then taken from frozen to cooked as quickly as possible. That approach minimizes the destructive potential of natural enzymes that reactivate during thawing. If you have taken the trouble to preserve foie gras at the peak of freshness, you definitely don't want to let it thaw slowly—and degrade—in the refrigerator overnight before you cook it.

Cooking straight from frozen obviously takes longer, often considerably longer, than cooking the same food from refrigerator temperature. Melting ice consumes an enormous amount of energy—much more than it takes to raise the same amount of water from 0 °C / 32 °F to 100 °C / 212 °F.

STRATEGIES FOR FREEZING

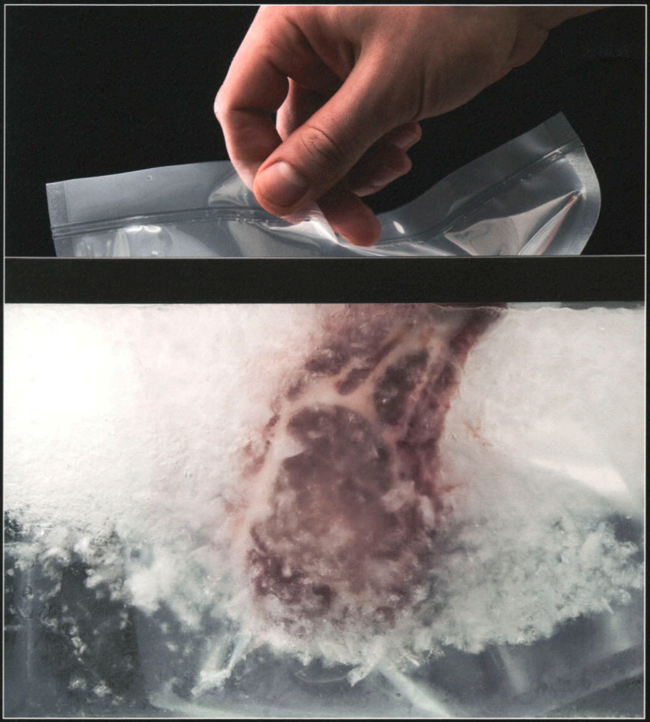
In general, the faster you can freeze food and store it while frozen, the better. But there are limits. Liquid nitrogen freezes all but the thinnest foods so quickly that they tend to crack open. Its extreme rate of freezing also damages meat and seafood, leaving them less juicy after thawing and cooking. The most convenient way to freeze food (although not to store it) is a simple brine of ice water and salt. Obviously a brine bath is suitable only for food in sous vide bags or other packaging that protects it from the salt. But for kitchens that do a lot of cooking sous vide, a brine bath is handy to have around.

Strategy	Cost	Pros	Cons
freezer	inexpensive	simple	slow food should be prechilled to avoid thawing frozen food nearby
ice-brine bath	very inexpensive	simple fast freezing rate	labor is required to make a brine and add ice freezes unevenly when overcrowded ice must be replenished food must be packaged
blast freezer	moderately expensive	moderately fast freezing high capacity	chamber is easily overcrowded
ultracold deep freezer	expensive	ideal for long-term storage	static air, although very cold, still freezes slowly food should be prechilled before freezing
liquid nitrogen	moderate	extremely fast freezing ideal for very small plant foods liquid nitrogen has other uses	very fast freezing causes many foods to crack and split makes meats and seafood less juicy when they are cooked or reheated requires very cold storage and special thawing to maintain benefits

HOW TO Freeze Food in a Salty Brine

Brine freezing is by far our favorite technique for rapidly freezing foods cooked sous vide. It works because the salt in the brine depresses the freezing point of water to well below its normal freezing point. Just how far below 0 °C / 32 °F is a function of the concentration of salt in the brine.

Why use ice brine to freeze vacuum-packed food? For the same reason that the seafood industry rapidly freezes valuable fish, such as bluefin tuna, in a mixture of saltwater and ice: the especially frigid water is more efficient than most other approaches at conducting heat out of the flesh, thus ensuring that a pricey food like this is preserved at peak quality. Rapid freezing is similarly beneficial for foods cooked sous vide that will be stored frozen.



Finely ground salt such as table salt (or less expensive canner's salt) dissolves much faster than coarsely ground rock salt does.

1 **Dissolve salt in warm water.** Add 400 g of salt for each 1 l / 1.1 qt of water. Salt dissolves slower as the concentration of salt increases, so the last bit of salt added to brine will take a long time to dissolve. This ratio of salt to water is near the limit of solubility, so stir diligently to fully dissolve the salt—any remaining on the bottom will take days to dissolve if left undisturbed. It is paramount that all of the added salt dissolve for the brine to reach the expected temperature when ice is added.

2 **For each liter of water used, add 1 kg / 2.2 lbs of ice.** Wait for about two-thirds of the ice to melt, which will yield 19% final brine strength and cause the temperature to plummet to about −15 °C / −5 °F as the ice melts.

3 **Submerge the packaged food.** Don't overcrowd the bath, and stir the packages of food around occasionally to prevent hot spots. Add more ice as the remaining ice melts, but be aware that this slowly dilutes the brine, and the effective freezing temperature rises accordingly.

4 **Remove the food once it has frozen.** Rinse and dry off the package, and store it frozen. Most damage to frozen food occurs after, not during, freezing as ice crystals grow larger and more damaging in food; the colder the frozen storage temperature, the better peak quality is preserved.

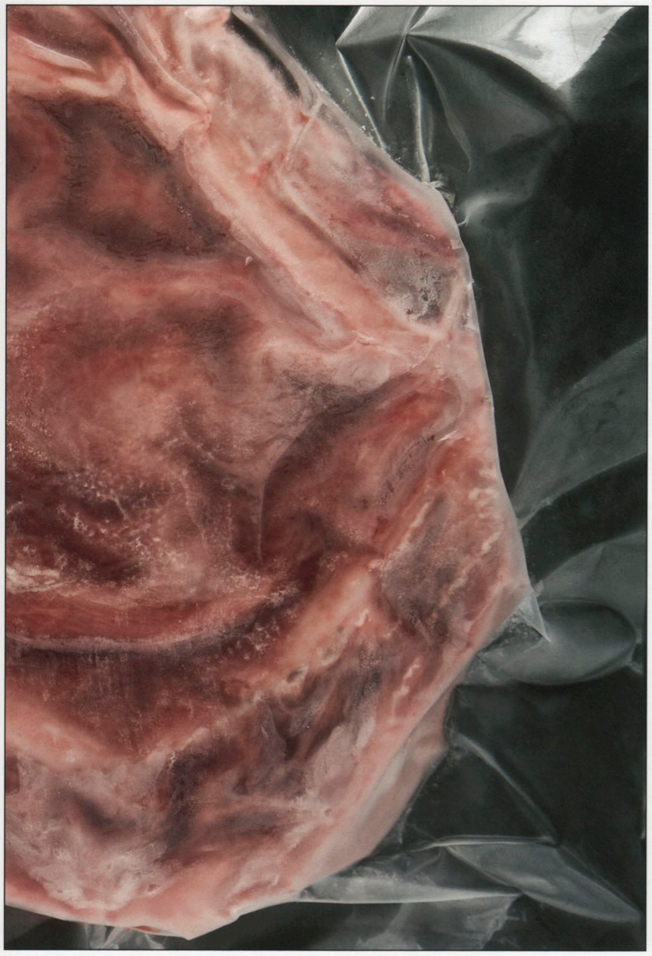
THE CHEMISTRY OF

Why Frozen Foods Change Flavor

Even after food is frozen, its flavor continues to change, and rarely for the better. One source of the change is the oxidation of fats and lipids, a process that eventually makes food smell rancid and taste warmed-over. The only way to (almost) halt these oxidative reactions is to evacuate all of the air from the food's packaging, then keep the food frozen at **cryogenic** temperatures. The extreme cold turns the water in food into a glass, essentially locking the reactive molecules in place, so they cannot join to make unpleasant flavors.

The flavor of food also changes when aromatic compounds are lost. Many of those compounds are volatile enough that they continue to evaporate, or sublimate, from the surface of food even while it is frozen. Here again, cryogenic freezing helps to preserve the fresh flavor of food by slowing these phenomena, and vacuum packaging contains any evaporating molecules like a second skin.

Unfortunately, no matter how cold the freezer or how tightly packaged the food, freezing will always cause some deterioration in flavor, for two reasons. First, as soon as the food is thawed, juices will escape and carry away some of the flavor. Second, freezing gradually but inexorably alters certain molecules in food, such as proteins. After thawing, they no longer capture and release taste and aroma compounds in quite the same way. The end result of that shift is to modify how we perceive the food's flavor.



Flavorful compounds dribble out of a frozen rib eye (at left, above) through what is known as drip loss. Ice crystals that formed in the steak as it froze now melt, and as their liquids leak from the meat (at right) they carry off compounds that give the meat some of its taste.

Rapid freezing and deep-cold storage can keep ice crystals small and minimize—but not eliminate—drip loss.

Moreover, thawing and freezing are not symmetrical processes. Thawing takes much longer because ice conducts heat better than liquid water does. So as fresh food freezes, the ice at the surface helps pull heat out of the food faster. But as frozen food thaws, meltwater on the surface insulates the ice below from the heat outside. Oddly enough, melting ice crystals sometimes even refreeze as food thaws.

Taken together, these two properties make it quite difficult to predict cooking times when cooking food from frozen. So it's imperative to cook in a bath set to the final core temperature, rather than to use some other cooking strategy. A hotter-than-core approach, for example, will probably either undercook or overcook the food because it's next to impossible to know how long it will take the frozen food to thaw.

For more on why thawing is so much slower than freezing, see page 1·311.

It is very important not to crowd a water bath when you cook directly from frozen. The extra energy it takes to thaw the frozen food will drop the temperature of the water bath (or other cooking environment). Within reason, the heating element can keep up with the drop, but with too much frozen food in the bath at one time, the temperature can dip too low.

It is also important that cooking directly from frozen be done at a bath temperature that is high enough to prevent bacterial growth—i.e. at or above 54 °C / 129 °F.

Reheating

Sous vide cooking was invented as a more convenient and economical way to organize the production of meals. Using sous vide, commercial kitchens could cook large quantities in advance then reheat individual portions only as needed. Large-scale advance preparation and reheating were not new to the restaurant business, but the extended storage time and higher quality retention that vacuum-packing and plastic bag technology delivered represented a breakthrough of sorts.

We feel nevertheless that some chefs are too fixated on the vacuum-packing step of sous vide, and they tend to miss the point of it. Most of the time, vacuum sealing food is a matter of convenience, not necessity; if the food is being prepared for immediate service, a restaurant gains order, cleanliness, and simplicity from vacuum packing. But that's about it.

Vacuum sealing does become important when food is cooked in advance and stored for future use. And in the real world of fine dining, efficient production and *mise en place* demand advance preparation. This arena is where sous vide shines. Precooking food sous vide is a useful strategy for synchronizing the cooking times of multicomponent dishes—such as those in volume 5—in which each component needs a different cooking time and temperature and, typically, further portioning, trimming, and seasoning after the initial cooking step.

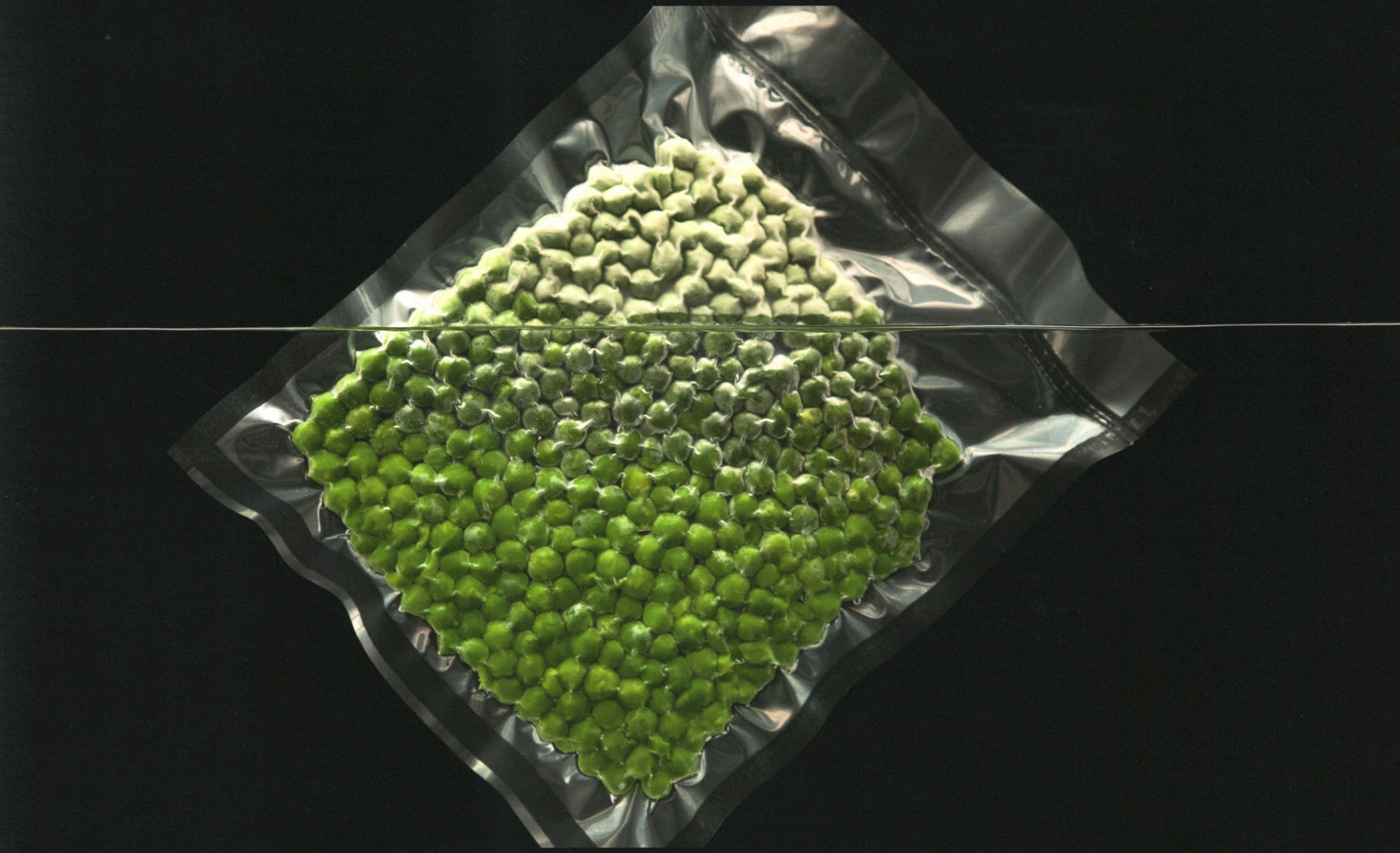
Consider, for example, our *pot-au-feu* recipe on page 5·49. It calls for several different meats, including a flatiron steak that needs relatively brief, low-temperature cooking, and a tough oxtail that needs lengthy cooking at a considerably

A whole turkey and similarly large foods warm slowly and unevenly, so they should not be left to thaw at room temperature. The pink tissue at the surface indicates that the outer part of the bird has warmed enough to create a hospitable environment for bacterial growth, even though the center of the turkey is still frozen hard. To be safe, thaw large food in a refrigerator or an ice bath.

STRATEGIES FOR THAWING

Too many cooks still use the traditional thawing method of warming frozen food in tepid water. Set aside the fact that this approach is hardly faster than thawing in ice water—the real problem is that by the time the center has thawed, the exterior may have spent far too long in the "danger zone" of warm temperatures at which bacteria reproduce readily. A much better alternative is to thaw in an ice-water bath or to begin cooking directly from the frozen state in a bath at cooking temperature (i.e., at or above 54 °C / 129 °F).

Strategy	Pros	Cons
ambient air	simple	slow suitable only for fast-thawing foods less than 10 cm / 4 in thick
refrigerator	safe easy recommended for large food	very slow, requiring days for very large pieces very slow thawing can damage the food
ice-water bath	fast safe easy suitable for large food	food usually must be sealed in waterproof packaging
cooked directly from frozen	convenient superior quality in some cases	requires long cooking times
tepid- or warm-water bath		only slightly faster at thawing than ice water not recommended: this strategy can leave the surface of thawing food dangerously warm, while the inside remains frozen



hotter temperature to gelatinize the collagen. Assorted root vegetables must be cooked separately at near-boiling temperatures to transform them from raw to cooked while preserving the integrity of their individual flavors.

Performing all these steps with traditional cooking techniques during a busy dinner service would be a challenge of the highest order. It is far simpler to cook each vegetable and type of meat sous vide, in advance, separately, and at just the right the temperature and time that suits it best. Sous vide techniques keep oxygen away from the food and simplify proper chilling, so each component of the dish retains its quality throughout lengthy and elaborate preparation. Later, the precooked components of the *pot-au-feu* can easily be reheated by using synchronized cooking times.

Three details are crucial to keep in mind when you reheat sous vide food. First, chilled food will take about the same amount of time to reach the target core temperature when reheated as it did when it was cooked from raw. Frozen food will take considerably more time. Thus, time savings occur only for foods that need to be held at temperature for long periods.

Second, take care not to overcook the food when you reheat it. All of your careful control of time and temperature during the cooking step will have been for naught if the reheating process goes off track.

The final tip is to rest the reheated food before serving it. Resting allows the exterior to cool slightly, and juices leaking at the surface then gel and thicken there. This step will preserve the flavor and moistness of the food.

Pot-au-feu exemplifies the most useful benefit of sous vide cooking, which is the flexibility it offers cooks to prepare ingredients in advance according to their individual requirements for cooking times and temperatures, portioning, trimming, and seasoning. The components can be stored and reheated simply and simultaneously for service.

Further Reading

Achatz, G. *Alinea*. Achatz, 2008.

Alleno, Y. 4 *Saisons à La Table No.5*. Glénat, 2006.

Baldwin, D. *Sous Vide for the Home Cook*. Paradox Press, 2010.

Blumenthal, H. *The Big Fat Duck Cookbook*. Bloomsbury USA, 2008.

Ducasse, A. *Grand Livre de Cuisine: Alain Ducasse's Culinary Encyclopedia*. Ducasse Books, 2009.

Fontane, J. B., Fontane, S. R. *Cocina Al Vacio*. Montagud, 2001.

Kamozawa, A., Talbot, A. H. *Ideas in Food: Great Recipes and Why They Work*. Clarkson Potter, 2010.

Keller, T. *Under Pressure: Cooking Sous Vide*. Artisan, 2008.

Logsdon, J. *Cooking Sous Vide: A Guide for the Home Cook*. CreateSpace, 2009.

Point, F. *Ma Gastronomie*. Overlook/Rookery, 2008.

Pralus, G. *Une Histoire d'Amour: La Cuisine Sous Vide*. Georges Pralus, 2000.

Roca, J., Brugus, S. *Sous Vide Cuisine*. Montagud, 2005.

Stampfer, V. *Sous Vide: Cooking in a Vacuum*. Matthaes, 2008.

Ideas in Food. ideasinfood.com

Cooking Issues. cookingissues.com

THE MARKETING OF

Reheat and Ready-to-eat

Precooked sous vide is a phenomenon of sorts well outside the temples of gastronomy. Cuisine Solutions and other companies have long been supplying airlines and retailers such as Costco with vacuum-packed meals that are ready to reheat and eat. The preparation and packaging techniques that Cuisine Solutions uses to make its sous vide meals would be quite familiar to Modernist cooks; the company simply deploys these techniques on a mind-boggling scale. It's not unusual, for example, for Cuisine Solutions to process 4.5 metric tons / 5 tons of chicken a week or to buy a million New Zealand lambs.

Although the meals are generally held to high standards of quality and safety, there are inevitable trade-offs. Its global market and the sheer volume of food it buys give Cuisine Solutions privileged access to certain ingredients—the New Zealand lamb, for example, and salmon from Argentina—but preclude the use of artisanal suppliers. Because the company can't control how its meals are stored or served and because those meals are likely to be consumed by millions of people, in the interest of safety, its kitchens tend to cook foods longer than a gastronome might advise. And even if the food hasn't overcooked to begin with, many a fine ready-to-eat dish has undoubtedly been ruined in the end through improper reheating. You won't find a water bath on most airplanes.

Nevertheless, sous vide—the pedestrian invention that started in the Swedish hospital system and moved on from there—is perfectly suited for institutional settings and other situations in which warm meals need to be served in bulk by people with no particular expertise in cooking.

Mass-market sous vide dinners extend the legacy of a technique that began as a means of producing meals in bulk for hospitals. The Cuisine Solutions brand is available at Costco and other retailers for home use. They also distribute to hotels, restaurants, and other caterers.

BLANCHING AND SEARING FOR SOUS VIDE

Cooking food sous vide consistently produces great-tasting food, but the appearance of the food after it comes out of the bag sometimes leaves a bit to be desired. Most people expect their beef steaks to be brown on the outside, not pink or gray. Grill marks on a fish steak add an appealing detail. Skin on a duck breast is better when crispy. All of these effects are impossible to achieve by sous vide cooking alone.

Fortunately, there is an easy way to get the best of both worlds: pairing sous vide cooking with the traditional techniques of blanching and searing. These techniques are useful for more than merely improving the look of the food. Both blanching and searing will sanitize the surface of food. Both will also firm up soft meats and seafoods so they hold their shape better when vacuum-packed. Blanching and searing are not always interchangeable, however. Blanching, for example, is always done before cooking sous vide, whereas you can sear ingredients before, after, or both.

Either steam or a brief dip into very hot water blanches food. The best way to avoid overcooking while blanching is to use water that is as hot as possible. That may seem counterintuitive, but it is true because heat takes time to penetrate food. The higher the temperature, the shorter the exposure to the water or steam needed to sanitize the food, and the less penetration of heat into the food. Water at 70 °C / 158 °F takes about 10 seconds to decontaminate the food surface, for example, whereas water at 76 °C / 168 °F achieves the same effect in just one second.

Using high-temperature steam or water at a rolling boil is especially important when blanching fruits and vegetables because high heat is needed to destroy enzymes as quickly as possible. Now, it is true that not all enzymes in plant tissue are bad; some do contribute to desirable flavors. But numerous other enzymes degrade produce as it is stored and cooked.

In green vegetables, for example, **chlorophyllase** gradually converts green **chlorophyll** into olive-brown **pheophytin pigments**. In many fruits and vegetables, such as apples, artichokes, and potatoes, **polyphenol oxidase** responds to tissue damage in much the same way that our skin tans in response to sunburn: by catalyzing the production of protective deep-brown **melanoidin pigments**. Vacuum packing and modified-atmosphere packing slows these enzymes down, but blanching long enough can destroy both polyphenol oxidase and chlorophyllase outright, thus better preserving the fresh color of fruits and vegetables.

For most fruits and vegetables, blanching at a full rolling boil is almost always preferable to steam blanching or simmering because it raises the temperature faster.

Quickly raising the core temperature to the boiling point is important because a temperature of 100 °C / 212 °F destroys 90% of the polyphenol oxidase enzymes in just two seconds, whereas it takes about two minutes to achieve that level of enzyme destruction at the slightly cooler temperature of 90 °C / 194 °F.

For more on why a rolling boil often heats faster than steam—and on the pros and cons of these two methods of blanching—see Boiling, page 63, and Steaming, page 70.

Quickly searing a steak on a plancha after cooking it in a water bath creates the mouth-watering aromas of charred meat while preserving the tenderness and juiciness that are hallmarks of sous vide cooking.

Searing Before Vacuum Packing

Searing food before vacuum sealing sometimes works better than blanching because the intense heat of searing triggers Maillard reactions that create many of the flavors we like in traditionally cooked foods (see page 3·89). Maillard reactions don't really get started until the temperature reaches at least 130 °C / 266 °F, well above that of a water bath. Once initiated, however, the reactions will continue even if the temperature decreases. Presearing can thus add depth to the flavor of sous vide dishes. This step should be avoided for lamb, other meats from grass-fed animals, and a few other foods in which presearing can trigger unwanted reactions that cause off-flavors and warmed-over flavors to form when the food is later cooked sous vide.

Presearing can be a convenient way to put grill marks on fish or chicken before bagging, thus simplifying the step of reheating for service. When a crisp crust is important, however, we must either postpone the searing until after sous vide cooking or sear the food again after the package is opened because any crust formed during presearing will soften during sous vide cooking.

For fatty meats such as duck breast, a special form of presearing called cryorendering (see page 3·124) can be especially useful. The temperatures at which we cook duck breasts sous vide typically aren't hot enough to render much of the fat beneath the skin. Searing the meat after cooking does render the fat, but at the cost of overcooking much of the meat. Cryorendering renders as much fat as possible from a near-frozen duck breast before the food is vacuum packed and cooked.

Here's a trick to get the rich flavors of searing without having to presear: save some of the trimmings from the meat or fish and cook them until brown and crispy, then pack the crispy trimmings around raw ingredients before you seal them in their bags. The Maillard flavors from the trimmings will continue to develop during cooking and will permeate the food they surround.

Keeping a skin crispy when the tender meat below is filled with juices can be tricky. One approach that we like to use for delicate fish is to remove the skin and dehydrate it separately to make a crispy wafer that can be served with the perfectly cooked fish from which it came.

Searing After Cooking

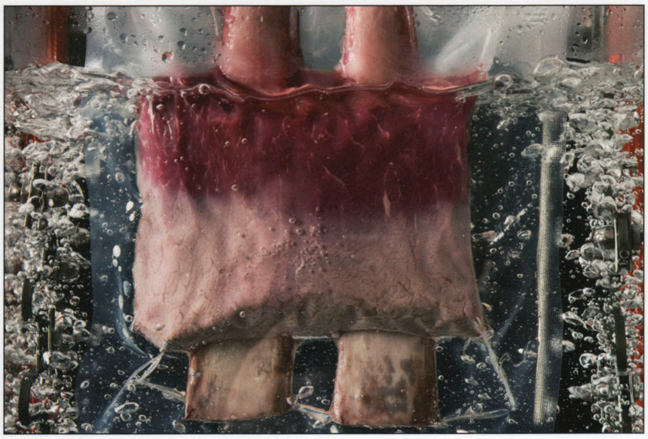
Some traditionalists have criticized sous vide cooking because, by itself, it doesn't always produce all the colors, flavors, and textures that older methods do, especially with meats and seafoods. Searing ingredients after they have been cooked sous vide solves this problem. Adding a final searing step to the sous vide process is simple and allows a cook to mimic the external result of any traditional cooking strategy while retaining and vastly improving control over how the interior cooks. Indeed, this hybrid form of cooking can create even more dramatic contrasts in texture between a crispy surface and the tender flesh beneath.

Searing also generates Maillard reactions and other chemical phenomena that occur only at high temperatures. The **tastants** and aromatic compounds produced by these complex reactions give roast beef, grilled chicken, and panfried salmon their unmistakable, irreplaceable flavors. Because sous vide cooking operates at lower temperatures to prevent meats and seafood from drying out, many of these flavor-creating reactions never occur within a sous vide cooker. But usually a judicious post-sous-vide sear can create the best of both worlds by browning the surface yet overcooking almost none of the underlying flesh.

There is one notable exception to this rule: crisping skin. Searing certainly crisps the surface of a piece of meat at first, but liquids from the juicy flesh beneath will quickly soak into the skin and make it soggy again. With duck breasts and a few other meats, you can leave a thin layer of fat between the crispy skin and the juicy meat to shield against moisture migration. Otherwise, we either try to dry out enough flesh between the dry surface and the juicy center to create a barrier or remove the skin altogether and crisp it separately.

The Pros and Cons of Blanching or Searing Before Cooking

Both the appearance and the flavor of many foods improved if they are blanched or seared before cooking sous vide. Both strategies increase the margin of food safety by eliminating bacterial contamination at its usual source: the surface of the food.



Blanching fruits and vegetables

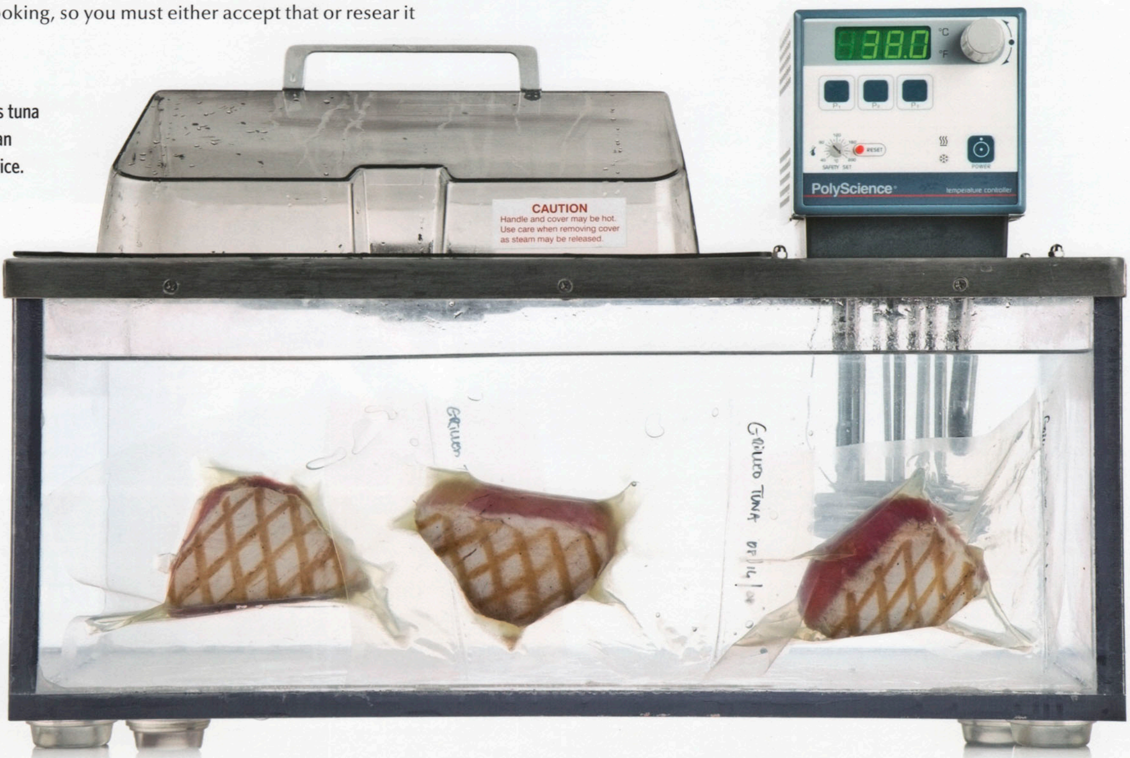
Pros: helps to preserve the color and texture of fresh produce
Cons: an additional step that may not be needed before cooking sous vide

Searing meats and seafood

Pros: decontaminates the surface, can improve Maillard flavors, and helps to render fat from meats cooked at low temperatures. Searing allows part of the finishing to be completed in advance
Cons: can lead to off-flavors in lamb and a few other meats. The crust will not be crisp after cooking, so you must either accept that or resear it

Blanching meats and seafood

Pros: decontaminates the surface and helps to preserve the shape of the food during later vacuum packing and cooking
Cons: an additional step that may not be necessary and that might overcook the surface



Presearing foods such as tuna steaks before cooking can sometimes simplify service.

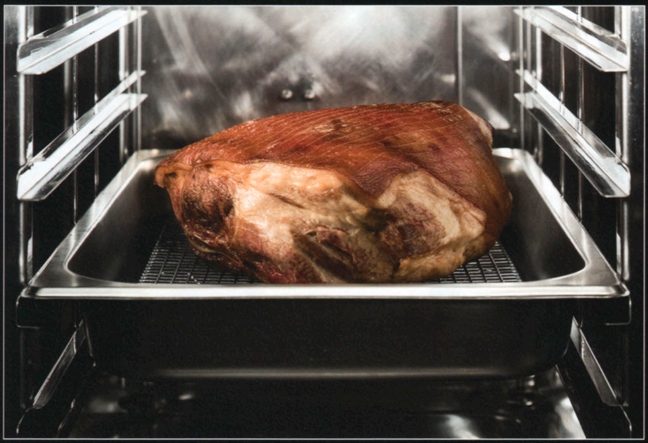
STRATEGIES FOR SEARING AFTER SOUS VIDE

Chefs can choose among numerous strategies for searing food they have cooked sous vide. Each method has strengths and weaknesses. In general, the larger the impulse of heat you can deliver, the better, because your goals are to brown the food surface quickly and to overcook as little of the flesh underneath as possible. The pros and cons of searing with a grill, oven, plancha, œ, broiler, torch, pan, and heat gun are summarized below.

Grilling

Pros: produces unique flavors and grill marks

Cons: flare-ups can be a hassle, although they are also an important source of flavor (see page 7)



Oven finishing

Pros: easy to do and can handle very large pieces of meat

Cons: slow; tends to overcook more of the meat

Plancha or griddle searing

Pros: as easy as searing but can generate higher temperatures. A griddle easily accommodates large portions or more pieces at once

Cons: relatively flat foods work best. Not appropriate for making a pan sauce

Deep frying

Pros: simple to do and browns very quickly and evenly. Useful for large or odd-shaped foods

Cons: if done poorly, it can make food greasier (see Cooking in Oil on page 2·115 for recommended techniques). Dealing with oil can be cumbersome

Broiling or salamander browning

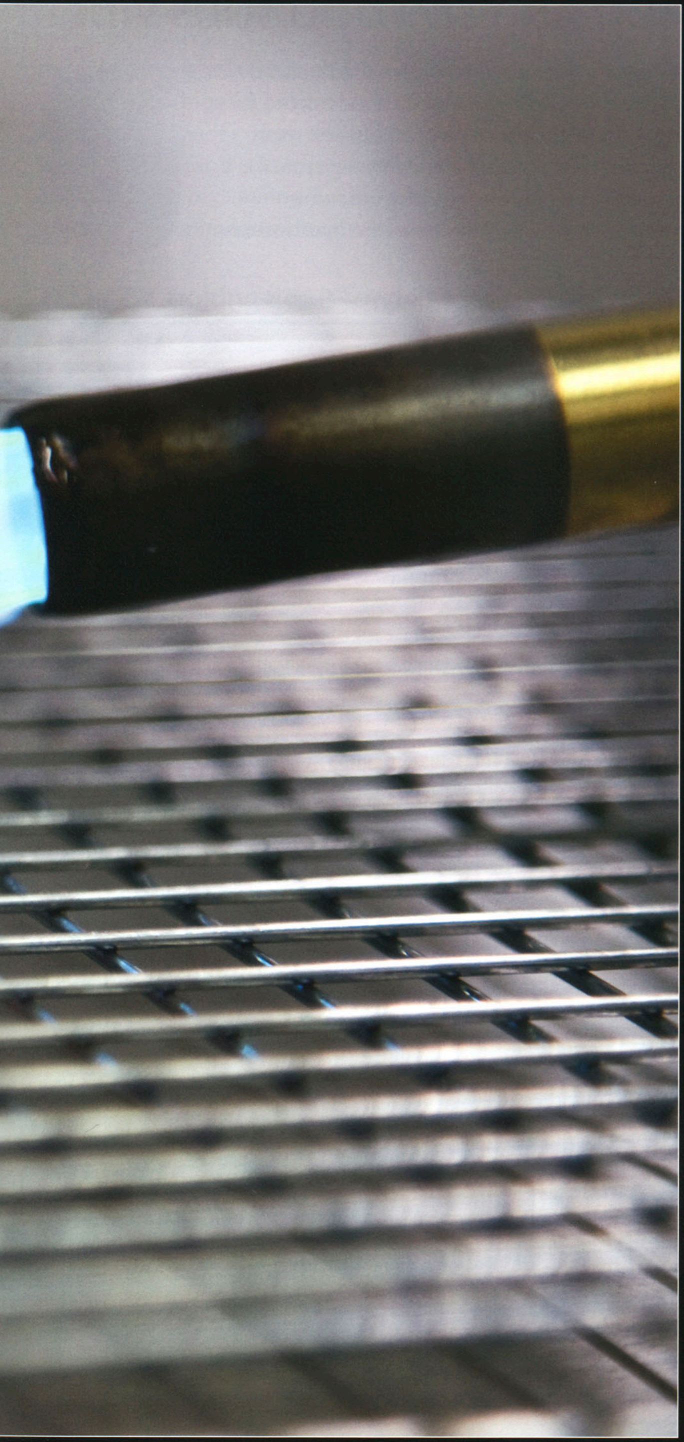
Pros: browning in a broiler is simple and can work for plated food

Cons: can produce uneven browning (see Broiling, page 18, for guidance on how to broil evenly in the sweet spot). Best when browning only the top of the food

Blow torching

Pros: ultrahigh heat sears faster than any other method and overcooks the least. Torching can brown areas that are difficult to reach with other methods, such as between a chicken leg and a breast

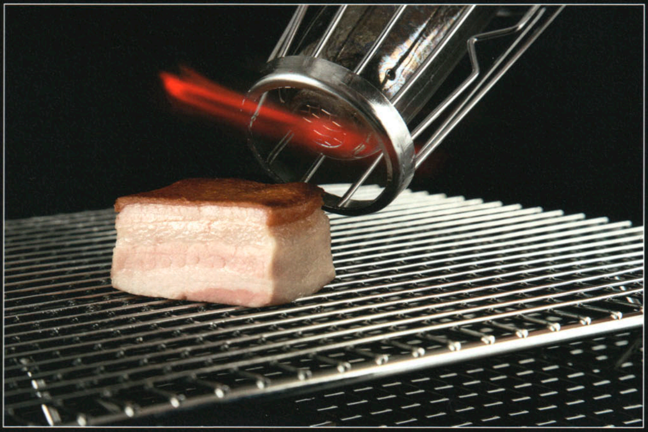
Cons: moderating browning can be tricky; it is easy to burn spots on the food. Torching is not time-efficient for searing large pieces of food. Incomplete combustion by torches can leave food tasting like gas; MAPP gas or oxyacetylene torches work better than propane or butane for producing high temperatures and no gas flavor



Panfrying

Pros: easy to do. Adding juices from the bag can yield an integral pan sauce

Cons: only works well on relatively small and flat foods. Pan searing also tends to be a bit slower than other methods; add a film of oil to the pan to boost heat transfer



Heat-gun browning

Pros: functioning much like a portable broiler, a heat gun produces more diffuse heat than a torch. Good for browning hard-to-reach areas

Cons: lower heat output extends searing times and makes it difficult to achieve deep browning

For more on torching, see How Not to Use a Blowtorch, page 21.

SUGGESTED TIMES FOR COOKING MEAT AND SEAFOOD SOUS VIDE

Sous vide cooking has many benefits, but it can be hard to estimate how long it will take. We used mathematical models, calibrated by experiments in our research kitchen, to produce the tables below. They offer estimated cooking times for foods of various shapes with the water bath set 1 °C / 2 °F higher than the core temperature you want the food to achieve (see page 246). The times are calculated for food having thermal properties typical of most meat and seafood, but they should be roughly accurate for most plant foods as well. Note that the times are approximate—because many variables are involved in

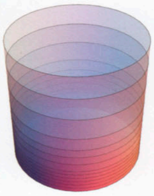


Table 1. Cooking times for cylinder-shaped meats having a diameter of 15 cm / 6 in

ΔT	Thickness (cm)													ΔT
(°C)	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.5	10.0	12.5	15.0	(°F)
5	3m 25s	8m 06s	14m 04s	21m 20s	29m 51s	39m 30s	1h 01m	1h 24m	1h 30m	2h 19m	3h 05m	3h 40m	4h 07m	9
10	4m 33s	10m 41s	18m 29s	27m 55s	38m 53s	51m 10s	1h 18m	1h 46m	2h 10m	2h 53m	3h 50m	4h 34m	5h 08m	18
15	5m 13s	12m 15s	21m 11s	31m 57s	44m 23s	58m 14s	1h 28m	1h 59m	2h 14m	3h 14m	4h 18m	5h 07m	5h 45m	27
20	5m 44s	13m 25s	23m 09s	34m 54s	48m 22s	1h 03m	1h 35m	2h 09m	2h 03m	3h 30m	4h 38m	5h 31m	6h 11m	36
25	6m 07s	14m 20s	24m 42s	37m 13s	51m 29s	1h 07m	1h 41m	2h 16m	2h 07m	3h 41m	4h 54m	5h 50m	6h 33m	45
30	6m 26s	15m 04s	25m 59s	39m 05s	54m 01s	1h 10m	1h 46m	2h 22m	2h 10m	3h 52m	5h 07m	6h 06m	6h 50m	54
35	6m 43s	15m 42s	27m 03s	40m 44s	56m 08s	1h 13m	1h 49m	2h 28m	3h 13m	4h 00m	5h 17m	6h 18m	7h 05m	63
40	6m 57s	16m 15s	27m 57s	42m 01s	57m 56s	1h 16m	1h 53m	2h 32m	3h 16m	4h 06m	5h 27m	6h 31m	7h 18m	72
45	7m 10s	16m 46s	28m 55s	43m 17s	59m 53s	1h 18m	1h 56m	2h 36m	3h 18m	4h 14m	5h 36m	6h 41m	7h 29m	81
50	7m 22s	17m 12s	29m 34s	44m 22s	1h 01m	1h 19m	1h 59m	2h 40m	3h 19m	4h 20m	5h 43m	6h 49m	7h 39m	90
55	7m 34s	17m 35s	30m 12s	45m 18s	1h 03m	1h 21m	2h 01m	2h 43m	3h 21m	4h 24m	5h 51m	6h 57m	7h 48m	99
60	7m 40s	17m 51s	30m 52s	46m 18s	1h 04m	1h 23m	2h 04m	2h 46m	3h 23m	4h 29m	5h 55m	7h 04m	7h 56m	108
65	7m 45s	18m 16s	31m 31s	47m 07s	1h 05m	1h 24m	2h 05m	2h 49m	3h 24m	4h 32m	6h 02m	7h 11m	8h 03m	117
70	7m 59s	18m 34s	32m 02s	48m 10s	1h 06m	1h 25m	2h 08m	2h 51m	3h 25m	4h 37m	6h 07m	7h 18m	8h 11m	126
75	8m 06s	18m 54s	32m 20s	48m 25s	1h 07m	1h 27m	2h 09m	2h 53m	3h 27m	4h 41m	6h 12m	7h 24m	8h 16m	135
80	8m 15s	19m 04s	32m 49s	49m 10s	1h 08m	1h 27m	2h 11m	2h 55m	3h 27m	4h 44m	6h 17m	7h 30m	8h 29m	144
85	8m 17s	19m 23s	33m 24s	49m 46s	1h 08m	1h 29m	2h 12m	2h 57m	3h 29m	4h 47m	6h 22m	7h 37m	8h 29m	153
90	8m 25s	19m 35s	33m 37s	50m 12s	1h 09m	1h 29m	2h 14m	3h 00m	3h 29m	4h 52m	6h 28m	7h 39m	8h 35m	162
95	8m 31s	19m 45s	33m 57s	50m 43s	1h 10m	1h 31m	2h 15m	3h 01m	3h 31m	4h 56m	6h 29m	7h 44m	8h 41m	171
100	8m 33s	19m 56s	34m 13s	51m 02s	1h 11m	1h 32m	2h 16m	3h 04m	3h 32m	4h 57m	6h 30m	7h 49m	8h 48m	180
105	8m 41s	20m 09s	34m 34s	52m 05s	1h 11m	1h 32m	2h 18m	3h 06m	3h 32m	4h 59m	6h 37m	7h 54m	8h 52m	189
110	8m 45s	20m 14s	35m 11s	52m 24s	1h 12m	1h 33m	2h 18m	3h 06m	3h 33m	5h 02m	6h 42m	7h 58m	8h 56m	198
115	8m 49s	20m 33s	35m 29s	53m 06s	1h 12m	1h 34m	2h 20m	3h 08m	3h 34m	5h 05m	6h 43m	8h 02m	9h 01m	207
120	8m 55s	20m 47s	35m 47s	54m 21s	1h 13m	1h 35m	2h 21m	3h 09m	3h 35m	5h 08m	6h 47m	8h 07m	9h 07m	216
125	9m 01s	20m 56s	35m 52s	53m 43s	1h 14m	1h 36m	2h 22m	3h 10m	4h 36m	5h 09m	6h 52m	8h 10m	9h 10m	225
130	9m 10s	21m 06s	36m 09s	54m 33s	1h 15m	1h 36m	2h 23m	3h 12m	4h 36m	5h 11m	6h 55m	8h 14m	9h 14m	234
	3⁄16	3⁄8	5⁄8	3⁄4	1	1⅛	1⅝	2	2⅜	3	4	5	6	
	Thickness (in)													

the calculations, this is not an exact guide and should not be relied upon for critical situations. A temperature probe provides more reliable information on how close the food is to being done, but the tables can be helpful in planning. For irregularly shaped foods, use the dimensions of the thickest part.

These tables were produced using a thermal diffusivity value of 0.13 mm²/s and a heat transfer coefficient of 100 W/m² · K. For more on these important thermodynamic parameters, see page 1·279.

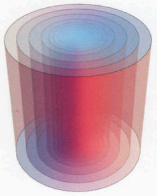


Table 2. Cooking times for cylinder-shaped meats having a length of 15 cm / 6 in

ΔT	Diameter (cm)												ΔT
(°C)	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.5	10.0	12.5	15.0	(°F)
5	3m 57s	6m 50s	10m 18s	14m 24s	19m 07s	30m 23s	44m 04s	59m 53s	1h 27m	2h 18m	3h 12m	4h 07m	9
10	5m 10s	8m 51s	13m 17s	18m 29s	24m 29s	38m 46s	56m 00s	1h 16m	1h 49m	2h 52m	3h 59m	5h 08m	18
15	5m 54s	10m 06s	15m 08s	21m 03s	27m 50s	43m 57s	1h 03m	1h 25m	2h 03m	3h 13m	4h 28m	5h 45m	27
20	6m 27s	11m 00s	16m 28s	22m 53s	30m 15s	47m 43s	1h 09m	1h 32m	2h 13m	3h 28m	4h 49m	6h 11m	36
25	6m 52s	11m 43s	17m 31s	24m 20s	32m 08s	50m 38s	1h 13m	1h 38m	2h 20m	3h 40m	5h 05m	6h 33m	45
30	7m 13s	12m 17s	18m 23s	25m 30s	33m 40s	53m 12s	1h 16m	1h 43m	2h 27m	3h 50m	5h 19m	6h 50m	54
35	7m 32s	12m 47s	19m 09s	26m 35s	35m 07s	55m 05s	1h 19m	1h 46m	2h 32m	3h 58m	5h 30m	7h 05m	63
40	7m 46s	13m 16s	19m 45s	27m 24s	36m 08s	56m 50s	1h 21m	1h 08m	2h 37m	4h 06m	5h 41m	7h 18m	72
45	7m 58s	13m 37s	20m 19s	28m 10s	37m 14s	58m 35s	1h 24m	1h 14m	2h 41m	4h 13m	5h 49m	7h 29m	81
50	8m 13s	13m 59s	20m 53s	28m 57s	38m 11s	1h 00m	1h 26m	1h 11m	2h 44m	4h 17m	5h 57m	7h 39m	90
55	8m 26s	14m 18s	21m 16s	29m 30s	38m 54s	1h 01m	1h 27m	1h 54m	2h 48m	4h 23m	6h 04m	7h 48m	99
60	8m 34s	14m 32s	21m 42s	30m 04s	39m 47s	1h 02m	1h 29m	1h 47m	2h 50m	4h 28m	6h 11m	7h 56m	108
65	8m 43s	14m 47s	22m 06s	30m 33s	40m 07s	1h 03m	1h 30m	2h 07m	2h 54m	4h 31m	6h 17m	8h 03m	117
70	8m 48s	15m 01s	22m 25s	30m 59s	40m 44s	1h 04m	1h 32m	2h 44m	2h 56m	4h 36m	6h 24m	8h 11m	126
75	8m 59s	15m 13s	22m 45s	31m 30s	41m 32s	1h 05m	1h 33m	2h 32m	2h 59m	4h 39m	6h 28m	8h 16m	135
80	9m 06s	15m 28s	23m 07s	31m 57s	42m 11s	1h 06m	1h 35m	2h 11m	3h 01m	4h 42m	6h 35m	8h 29m	144
85	9m 15s	15m 42s	23m 30s	32m 31s	42m 43s	1h 07m	1h 36m	2h 43m	3h 03m	4h 48m	6h 39m	8h 29m	153
90	9m 22s	15m 50s	23m 38s	32m 46s	43m 15s	1h 07m	1h 36m	2h 15m	3h 06m	4h 49m	6h 41m	8h 35m	162
95	9m 27s	16m 05s	23m 52s	33m 07s	43m 53s	1h 09m	1h 38m	2h 53m	3h 07m	4h 52m	6h 45m	8h 41m	171
100	9m 32s	16m 18s	24m 16s	33m 36s	44m 17s	1h 09m	1h 38m	2h 17m	3h 08m	4h 55m	6h 50m	8h 48m	180
105	9m 42s	16m 19s	24m 25s	33m 47s	44m 27s	1h 10m	1h 39m	2h 27m	3h 10m	4h 58m	6h 55m	8h 52m	189
110	9m 44s	16m 30s	24m 31s	34m 03s	44m 53s	1h 10m	1h 40m	2h 53m	3h 13m	5h 00m	6h 57m	8h 56m	198
115	9m 49s	16m 36s	24m 47s	34m 06s	45m 15s	1h 11m	1h 41m	2h 15m	3h 13m	5h 03m	7h 01m	9h 01m	207
120	9m 52s	16m 47s	25m 03s	34m 42s	45m 43s	1h 12m	1h 43m	2h 43m	3h 15m	5h 07m	7h 04m	9h 07m	216
125	10m 00s	16m 57s	25m 20s	35m 04s	46m 17s	1h 12m	1h 43m	2h 17m	3h 18m	5h 09m	7h 03m	9h 10m	225
130	10m 06s	17m 06s	25m 23s	35m 07s	46m 27s	1h 13m	1h 44m	2h 27m	3h 19m	5h 10m	7h 11m	9h 14m	234
	⅜	⅝	¾	1	1⅛	1⅝	2	2⅜	3	4	5	6	

Diameter (in)

SUGGESTED TIMES FOR COOKING MEAT AND SEAFOOD SOUS VIDE

continued

HOW TO Use the Sous Vide Tables

1 **Calculate ΔT by subtract the starting temperature of the food from the desired final temperature.**

2 **Choose the table that best fits the shape of the food.** For disc-like foods that are roughly circular and about 15 cm / 6 in. in diameter, use table 1. For long, cylindrical foods (like sausages) that are 15 cm / 6 in or longer, use table 2. For cubes, spheres, or squat cylinders, use table 3. For slabs much longer than they are thick, use table 4.

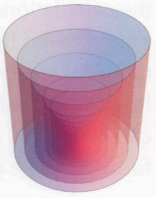


Table 3. Cooking times for cylinder-shaped meats having thickness roughly equal to their diameter

ΔT	Thickness and diameter (cm)													ΔT
(°C)	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.5	10.0	12.5	15.0	(°F)
5	15s	0m 58s	2m 11s	3m 53s	6m 04s	8m 45s	15m 33s	24m 17s	34m 59s	54m 39s	1h 37m	2h 32m	3h 39m	9
10	18s	1m 12s	2m 43s	4m 50s	7m 33s	10m 52s	19m 19s	30m 10s	43m 27s	1h 08m	2h 01m	3h 09m	4h 32m	18
15	20s	1m 21s	3m 03s	5m 24s	8m 27s	12m 10s	21m 38s	33m 48s	48m 40s	1h 16m	2h 15m	3h 31m	5h 04m	27
20	22s	1m 28s	3m 17s	5m 50s	9m 07s	13m 07s	23m 19s	36m 26s	52m 28s	1h 22m	2h 26m	3h 48m	5h 28m	36
25	23s	1m 33s	3m 28s	6m 10s	9m 38s	13m 53s	24m 40s	38m 32s	55m 30s	1h 27m	2h 34m	4h 01m	5h 47m	45
30	24s	1m 37s	3m 37s	6m 26s	10m 03s	14m 28s	25m 47s	40m 13s	57m 55s	1h 30m	2h 41m	4h 11m	6h 02m	54
35	25s	1m 40s	3m 45s	6m 39s	10m 24s	14m 57s	26m 38s	41m 37s	59m 56s	1h 34m	2h 46m	4h 20m	6h 15m	63
40	26s	1m 43s	3m 52s	6m 52s	10m 43s	15m 26s	27m 26s	42m 52s	1h 02m	1h 36m	2h 51m	4h 28m	6h 26m	72
45	27s	1m 46s	3m 58s	7m 03s	11m 00s	15m 51s	28m 10s	44m 02s	1h 03m	1h 39m	2h 56m	4h 35m	6h 36m	81
50	27s	1m 48s	4m 03s	7m 12s	11m 14s	16m 11s	28m 40s	44m 47s	1h 04m	1h 41m	2h 59m	4h 40m	6h 43m	90
55	28s	1m 50s	4m 08s	7m 20s	11m 28s	16m 30s	29m 23s	45m 53s	1h 06m	1h 43m	3h 04m	4h 47m	6h 53m	99
60	28s	1m 52s	4m 12s	7m 28s	11m 40s	16m 47s	29m 48s	46m 39s	1h 07m	1h 45m	3h 07m	4h 52m	7h 00m	108
65	29s	1m 54s	4m 17s	7m 37s	11m 54s	17m 07s	30m 27s	47m 33s	1h 08m	1h 48m	3h 10m	4h 57m	7h 08m	117
70	29s	1m 56s	4m 21s	7m 43s	12m 04s	17m 23s	30m 51s	48m 09s	1h 09m	1h 48m	3h 13m	5h 01m	7h 14m	126
75	29s	1m 57s	4m 24s	7m 50s	12m 13s	17m 37s	31m 21s	48m 57s	1h 10m	1h 50m	3h 16m	5h 06m	7h 20m	135
80	30s	1m 59s	4m 28s	7m 56s	12m 24s	17m 52s	31m 41s	49m 35s	1h 11m	1h 52m	3h 18m	5h 10m	7h 26m	144
85	30s	2m 00s	4m 30s	8m 00s	12m 29s	17m 59s	31m 56s	50m 04s	1h 12m	1h 53m	3h 20m	5h 12m	7h 29m	153
90	30s	2m 02s	4m 32s	8m 06s	12m 39s	18m 14s	32m 24s	50m 39s	1h 13m	1h 54m	3h 22m	5h 16m	7h 35m	162
95	31s	1m 59s	4m 36s	8m 12s	12m 48s	18m 27s	32m 44s	51m 14s	1h 14m	1h 55m	3h 25m	5h 20m	7h 41m	171
100	31s	2m 00s	4m 39s	8m 15s	12m 55s	18m 36s	33m 06s	51m 42s	1h 15m	1h 56m	3h 27m	5h 23m	7h 45m	180
105	31s	2m 05s	4m 44s	8m 22s	13m 03s	18m 51s	33m 33s	52m 24s	1h 16m	1h 58m	3h 29m	5h 27m	7h 51m	189
110	32s	2m 07s	4m 45s	8m 26s	13m 11s	18m 59s	33m 46s	52m 46s	1h 16m	1h 59m	3h 31m	5h 29m	7h 55m	198
115	32s	2m 07s	4m 46s	8m 27s	13m 14s	19m 01s	33m 50s	52m 47s	1h 16m	1h 59m	3h 31m	5h 30m	7h 55m	207
120	32s	2m 08s	4m 48s	8m 32s	13m 19s	19m 09s	34m 03s	53m 05s	1h 16m	1h 59m	3h 32m	5h 32m	7h 58m	216
125	32s	2m 09s	4m 50s	8m 37s	13m 29s	19m 21s	34m 24s	53m 47s	1h 17m	2h 01m	3h 35m	5h 36m	8h 04m	225
130	33s	2m 10s	4m 52s	8m 38s	13m 29s	19m 26s	34m 32s	53m 51s	1h 17m	2h 01m	3h 36m	5h 37m	8h 06m	234
	3⁄16	⅜	⅝	¾	1	1⅛	1⅝	2	2⅜	3	4	5	6	

Thickness and diameter (in)

3 **Look up the cooking time given for the ΔT you calculated and the relevant dimension of the food.**

4 **Cook the food in a water bath set to 1 °C / 1.8 °F above the desired final temperature, for the time given.** If you want to pasteurize, you must look up pasteurization time for the desired final temperature and add this to the cooking time listed in the table.

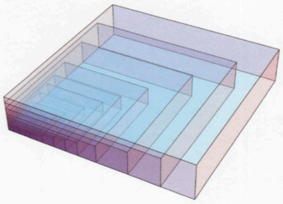


Table 4. Cooking times for slabs of meat whose width and length is at least five times the thickness

ΔT	Thickness (cm)													ΔT
(°C)	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.5	10.0	12.5	15.0	(°F)
5	40s	2m 38s	5m 56s	10m 33s	16m 30s	23m 45s	42m 13s	1h 06m	1h 45m	2h 28m	4h 24m	6h 52m	9h 54m	9
10	51s	3m 26s	7m 42s	13m 42s	21m 24s	30m 49s	54m 47s	1h 26m	2h 49m	3h 13m	5h 42m	8h 55m	12h 50m	18
15	59s	3m 55s	8m 48s	15m 39s	24m 26s	35m 14s	1h 03m	1h 38m	2h 14m	3h 40m	6h 31m	10h 12m	14h 41m	27
20	1m 04s	4m 16s	9m 35s	17m 03s	26m 38s	38m 21s	1h 08m	1h 47m	2h 21m	4h 00m	7h 06m	11h 06m	15h 59m	36
25	1m 08s	4m 33s	10m 13s	18m 09s	28m 21s	40m 49s	1h 13m	1h 53m	2h 49m	4h 15m	7h 34m	11h 49m	17h 01m	45
30	1m 12s	4m 46s	10m 44s	19m 04s	29m 48s	43m 01s	1h 16m	1h 59m	2h 01m	4h 29m	7h 58m	12h 27m	17h 56m	54
35	1m 14s	4m 58s	11m 09s	19m 49s	31m 05s	44m 47s	1h 20m	2h 04m	2h 47m	4h 40m	8h 18m	12h 57m	18h 39m	63
40	1m 17s	5m 07s	11m 32s	20m 34s	32m 08s	46m 15s	1h 22m	2h 08m	3h 15m	4h 49m	8h 34m	13h 23m	19h 16m	72
45	1m 19s	5m 16s	11m 52s	21m 05s	32m 56s	47m 26s	1h 24m	2h 12m	3h 26m	4h 56m	8h 47m	13h 44m	19h 46m	81
50	1m 21s	5m 25s	12m 12s	21m 42s	33m 56s	48m 49s	1h 27m	2h 16m	3h 49m	5h 05m	9h 03m	14h 08m	20h 21m	90
55	1m 23s	5m 31s	12m 27s	22m 06s	34m 31s	49m 45s	1h 28m	2h 18m	3h 45m	5h 11m	9h 12m	14h 23m	20h 44m	99
60	1m 25s	5m 38s	12m 40s	22m 31s	35m 10s	50m 38s	1h 30m	2h 21m	3h 38m	5h 17m	9h 23m	14h 40m	21h 06m	108
65	1m 26s	5m 45s	12m 56s	22m 58s	35m 54s	51m 40s	1h 32m	2h 23m	3h 40m	5h 23m	9h 34m	14h 57m	21h 31m	117
70	1m 28s	5m 49s	13m 11s	23m 25s	36m 35s	52m 38s	1h 34m	2h 26m	3h 38m	5h 29m	9h 45m	15h 14m	21h 56m	126
75	1m 29s	5m 56s	13m 21s	23m 42s	37m 00s	53m 15s	1h 35m	2h 28m	3h 15m	5h 34m	9h 53m	15h 27m	22h 14m	135
80	1m 30s	6m 01s	13m 33s	24m 05s	37m 37s	54m 11s	1h 36m	2h 31m	3h 11m	5h 39m	10h 03m	15h 42m	22h 34m	144
85	1m 31s	6m 06s	13m 44s	24m 25s	38m 12s	55m 02s	1h 38m	2h 33m	3h 02m	5h 44m	10h 12m	15h 54m	22h 54m	153
90	1m 32s	6m 10s	13m 53s	24m 39s	38m 34s	55m 29s	1h 39m	2h 34m	3h 29m	5h 47m	10h 16m	16h 05m	23h 08m	162
95	1m 33s	6m 13s	13m 58s	24m 50s	38m 42s	55m 41s	1h 39m	2h 35m	3h 41m	5h 48m	10h 19m	16h 08m	23h 13m	171
100	1m 35s	6m 16s	14m 08s	25m 05s	39m 10s	56m 25s	1h 40m	2h 36m	3h 25m	5h 53m	10h 26m	16h 20m	23h 29m	180
105	1m 35s	6m 21s	14m 18s	25m 22s	39m 38s	57m 06s	1h 42m	2h 39m	3h 06m	5h 57m	10h 35m	16h 31m	23h 48m	189
110	1m 36s	6m 26s	14m 30s	25m 43s	40m 12s	57m 57s	1h 43m	2h 41m	3h 57m	6h 02m	10h 43m	16h 45m	24h 07m	198
115	1m 37s	6m 28s	14m 28s	25m 42s	40m 14s	57m 56s	1h 43m	2h 41m	3h 56m	6h 02m	10h 43m	16h 46m	24h 06m	207
120	1m 38s	6m 31s	14m 38s	25m 57s	40m 36s	58m 20s	1h 44m	2h 42m	3h 20m	6h 05m	10h 48m	16h 53m	24h 19m	216
125	1m 39s	6m 34s	14m 48s	26m 14s	41m 00s	59m 09s	1h 45m	2h 44m	3h 09m	6h 09m	10h 57m	17h 07m	24h 36m	225
130	1m 40s	6m 37s	14m 55s	26m 27s	41m 23s	59m 30s	1h 46m	2h 45m	3h 30m	6h 11m	11h 02m	17h 12m	24h 47m	234
	3⁄16	3⁄8	5⁄8	3⁄4	1	1 1⁄8	1 5⁄8	2	2 3⁄8	3	4	5	6	
	Thickness (in)													

THE MODERNIST KITCHEN 10

① Chamber-style vacuum sealer
② Rotary evaporator
③ Circulated heating water bath
④ Diaphragm pump
⑤ Circulated heating–chilling water bath
⑥ Ultrahigh-pressure homogenizer
⑦ Rotor-stator homogenizer
⑧ Handheld ultrasonic homogenizer
⑨ Vacuum pump
⑩ Rational brand combi oven
⑪ Uncirculated heating water baths
⑫ Digital scale
⑬ Centrifuge
⑭ Carbon dioxide gas tank
⑮ Lab sieves
⑯ Centrifugal juicer
⑰ Standing mixer
⑱ Thermomix brand heated blender
⑲ Anti-Griddle freezing surface
⑳ Carpigiani brand ice cream machine
㉑ High-power gas burner
㉒ Chamber-style vacuum sealer
㉓ Commercial blender
㉔ Automatic pasta machine

10

THE MODERNIST KITCHEN

Most cooking techniques use heat to make food more appetizing. This chapter explores various other ways to prepare food that do not use heat—at least not in a conventional manner. From sieving and straining to fining and filtering to juicing, drying, and freezing, Modernist cooks have been pushing beyond what is commonly done in kitchens to extract and concentrate flavor. Inspired in some cases by the technological tools and techniques that scientists use, pioneering cooks have found ways to directly apply equipment such as rotary evaporators, centrifuges, and homogenizers to solve culinary problems and to create special effects with food.

Even if you never have the opportunity to use some of these relatively high-tech devices, it's worth understanding how they work because you can sometimes use less-sophisticated tools to apply the same principles these high-end machines exploit. Heston Blumenthal and his research staff at The Fat Duck restaurant in Bray, U.K., for example, were able to make stocks both faster and better-tasting once they grasped the implications of Fick's laws of diffusion, which describe how flavor compounds move through meat and vegetable tissues. Those fundamental ideas led them to start making stocks in pressure cookers, which greatly speed the notoriously time-consuming process and enrich the flavor to boot.

The amazing variety of new tools moving from the laboratory to the kitchen is both a bit humbling and tremendously exciting. It is humbling because it forces us to acknowledge that all the cooks who have ever lived during human history have really only scratched the surface of possible culinary experiences. The wonderful range of food created by the world's cuisines and the innumerable creative ideas developed by countless cooks over millennia are merely the beginning for the Modernist cook. It is exciting because the new tools create paths into that vast universe of eating experiences still to be discovered. As the next generation of chefs masters and then improves these tools and techniques, they will continue to take cuisine in novel and revolutionary directions.

Modernist cooking does not displace traditional methods—it builds on them. In a Modernist kitchen, you'll find the basic food ingredients that all cooks use. But you'll also see newer components that offer special effects: concentrated flavor extracts, spray-dried food and flavor powders, gelling agents, cryogenic fluids, inert gases, and so on. These less familiar ingredients are nearly all derived from natural sources (see page 1·257) but were largely unknown to cooks a century ago.

The Modernist cook still performs many traditional tasks in preparing, combining, and otherwise transforming ingredients into dishes—but does so without all the compromises that cooks have traditionally had to accept. The new know-how and equipment borrowed from

Fantastic new equipment that enables new kinds of food to be made is one of the joys of Modernist cooking. But you still need skill, and you still need most traditional kitchen equipment.

Must-Have Tools for the Modernist Kitchen

In making this book, we had the opportunity to work with many different kinds of equipment. Some of the tools we purchased; others were sent on loan or donated to be cut in half. All that experience has left us with some favorite kinds of tools and techniques that we feel are must-haves for practicing Modernist cooking. Below is our top-ten list, ranked so that those items that offer the greatest value for the price appear higher on the list. If used properly, these tools will eventually pay for themselves in convenience and results. Not all available brands are listed; those given are the ones used in our research kitchen, arranged from least to most expensive. In most cases there are other manufacturers who offer similar products, which may be as good or better.

Rank	Tool	Kind	Brand	2010 price, new	See page	Note
1	water bath	nonstirred	SousVide Supreme, VWR	$500	232	the best tool for cooking sous vide or for any cooking task that requires precise temperature control; it is useful to have several baths for preparing several dishes at different temperatures simultaneously
		circulating	PolyScience, Lauda, other	$1,000–$2,000		
2	liquid nitrogen	Dewar flask	Thermo Scientific	$500–$1,000	456	useful for myriad prep tasks and for producing special effects
3	modern oven	combi	Rational, other	$10,000 and up	162	the kitchen's most versatile tool
		water-vapor	Winston CVap, Accu-Steam	$5,000	158	effective for some combi oven tasks or for sous vide with or without bags
4	sealer	impulse (no vacuum)	Hualian	$50	225	vacuum sealing greatly improves the precision and flexibility of cooking in water baths and combi ovens, and sealers are also useful for preserving, compressing, and expanding foods; chamber sealers are best
		edge vacuum	FoodSaver	$100	222	
		chamber vacuum	Henkelman, ARY, Multivac	$1,500–$3,500	214	
5	homogenizer	rotor-stator	Omni, IKA	$1,000- $5,000	413	a tabletop homogenizer produces the smoothest and most stable sauces, purees, and emulsions
		colloid mill	IKA, Chinese brands	$3,500–$30,000	413	
		high-pressure	Avestin	$10,000–$30,000	414	
6	Pacojet		Pacojet	$3,500	406	this powerful grinder makes ice cream, superfine pastes, and purees
7	vacuum pump	faucet aspirator	Nalgene	$20–$100	356	useful for filtering and desiccation; faucet aspirators save on cost but waste water
		motorized aspirator	Brinkmann, Oakton	$700		
		membrane	Büchi	$500–$2,000		
8	magnetic stirrer with hot plate	laboratory	Corning, Cimarec, IKA	$300	380	useful for temperature-controlled heating and stirring tasks, such as dispersing and hydrating hydrocolloids
		digital		$500		
9	centrifuge		Beckman Coulter, Sorvall (now Thermo Scientific)	$10,000–$30,000	360	useful for rapidly and thoroughly clarifying liquids and separating fats
10	autoclave		Yamato, Tuttnauer	$3,000–$8,000	239	an incredibly useful automated pressure cooker; comes in many sizes

Handy Special-Purpose Tools

Although we would suffer without a good smoker, and we love our peristaltic pump, they don't get used every day as our must-have tools do. Not every kitchen needs the kinds of tools listed below, but they fulfill their special roles with excellent usability and performance. Brands listed are those we have used in our research kitchen.

Rank	Item	Kind	Brand or model	2010 price, new	See page	Note
1	ultrasonic bath		Branson	$500–$1,000	302	cleans small items, extracts locked-in flavors
2	vacuum tumbler		any	$500–$2,000	3·166	accelerates brining, curing, and marinating of meats
3	blast chiller		any	$1,000 and up	1·310	chills large amounts of food; useful for quickly chilling items cooked sous vide
4	smoker	sawdust puck smoker	Bradley	$700	146	uses a hopper and sawdust pucks; electrically heated
		pellet hot smoker	Traeger, Cookshack FEC 100	$500–$3,700		uses wood pellets; generates a particular kind of smoke and temperature performance
		computer controller for custom smoker	BBQ Guru	$300 and up		converts an existing smoker into one with digital control
		digital smoke oven with humidity control and cold-smoking capability	Enviro-Pak	$30,000		features full digital control of temperature and humidity
5	freeze dryer	taxidermy or florist grade	Freeze Dry Co.	$12,500	444	freeze-dries foods for extended storage or to enhance flavors in unique ways
		pharmaceutical grade	VirTis	$50,000 and up		
6	rotary evaporator		Büchi, Yamato	$10,000 and up	386	makes essential oils, extracts, and alcohols
7	chilling water bath		PolyScience	$3,000–$4,000	238	cools foods to precise temperatures; useful when cooking sous vide
8	vacuum oven		Fisher Scientific	$3,500	4·310	bakes the lightest meringue imaginable
9	meat band saw		Hobart	$500–$3,000		useful for butchering whole animals and meat cuts for stockmaking
10	peristaltic pump		Masterflex	$1,200	4·139	useful for making long gel noodles
11	spray dryer		Yamato	$17,000	438	makes fine powders from any liquid
12	vacuum concentrator		Genevac Rocket Evaporator	$20,000	381	reduces sauce and stock; very low heat yields bright flavors

The prices listed here are typical for new equipment in 2010, but over time these surely will change. In addition, much of this equipment is available secondhand on eBay or from used scientific equipment dealers at a substantial discount.

tories and food processing plants make it possible for Modernist chefs to realize a larger fraction of what they can imagine.

This new power over food can be a little addictive. If there is a danger in the Modernist kitchen, it is that all the novel tools and ingredients tempt you to make something surprising or unfamiliar—but not necessarily good—just because you can. The best Modernist chefs temper their enthusiasm for the new with a refined palate and a sense of humor about their work. The parts of this amazing new world that they share with their guests are not merely novel but also a delight to see, smell, touch, and eat.

Inexpensive but Invaluable Modernist Tools

Gadgets? Not exactly. These are items that we have come to rely on for efficiency and consistent results. Scales, silicone molds, siphons, blowtorches, and lab sieves; we can't imagine cooking without them.

Rank	Tool	Kind	Brand	2010 price, new	Note
1	digital scale	5 kg maximum, 1 g increments	Ohaus	$150–$250	a must-have; every recipe in this book requires accurate weighing
		200 g maximum, 0.01 g increments	Ohaus	$200–$500	
2	thermometer	pocket digital thermistor	Thermapen	$70–$100	a must-have; precise temperature control is crucial in Modernist cooking
		infrared	Fluke	$75–$200	
3	pressure cooker		Kuhn Rikon	$200	a must-have; essential for stocks, tenderizing tough grains and seeds
4	blowtorch	MAPP gas or propane	TurboTorch	$50	MAPP gas makes it easier to avoid tainting food with combustion products
		oxyacetylene	Lenox	$200	
5	lab sieves	assorted sizes	Newark	$75	sieves to very fine levels with little fuss or expense
6	foam-whipping siphons		iSi	$100	professional-grade models with durable motors are best
7	hand blender	stick type	Bamix, Bosch	$80–$175	
8	silicone mats	half-sheet and full-sheet size	Silpat	$20	useful for food that sticks
9	surgical forceps		any	$10–$30	have several sizes on hand
10	meat tenderizer	handheld	Jaccard	$40	
11	dehydrator	with Para-Flexx sheets	Excalibur	$100- $500	
12	vacuum desiccator	Nalgene	any	$100–$200	
13	vacuum-filtering setup	filter flask, Büchner funnel, filter media, and pump	Whatman (media)	$200–$500	useful for clarifiying broth or consommé
14	vacuum jars	assorted sizes	FoodSaver	$15	
15	meat slicer	commercial grade	Biro, Berkel	$150–$450	
16	silicone molds	assorted sizes	any	$20	a must-have for casting gels and setting shapes
17	carbonator	soda siphon	any	$200–$300	for do-it-yourself soda
18	skin-puncturing tool	wire brush	any	$5–$10	useful for quickly perforating pastry or skin
19	pressure-filtering kit		Buon Vino	$200–$300	clarifies liquids quickly with minimal waste or flavor change
20	coffee cold-brewing kit		Toddy	$30	makes full-flavored extracts for use in cooking

Classic Tools for Modernist Cooks

Not everything has to be cutting edge. Some traditional tools, such as a wok burner and a griddle, will always have a place in our kitchen. In selecting traditional tools, we focused on price, quality, and efficiency. Good prices can often be found on refurbished or used items. The brands listed are those we used; many others are available.

Rank	Tool	Kind or grade	Brand	2010 price, new	Note
1	cooktop	1,800 W induction	Sunhom, Sunpentown, others	$200	can handle most needs filled by traditional ranges
		3–5 kW induction	Thirode, others	$1,000 and up	
2	broiler	gas catalytic	TEC, others	$2,000	
		electric	DeLonghi, Star-Max	$150–1,500	
3	blender	commercial	Vita-Mix, Waring	$400	commercial blenders are faster and produce smoother results
4	microwave oven	commercial	Amana, Panasonic, others	$200–$1,000	
5	mixer	stand	KitchenAid, Hobart	$500	
6	milk shake machine	commercial	Waring	$200	useful for creating thick foams
7	griddle (*plancha*)	commercial	Accu-Steam, others	$4,000	
8	deep fryer	commercial	Waring	$400	
9	wok burner	commercial	Imperial, Viking	$1,000	useful when high heat output is necessary
10	espresso machine	commercial	Synesso	$8,000	the best-built espresso machine we have tried
11	espresso grinder	commercial	Mazzer	$750	the grinder is as important as the espresso machine

EXTRACTING FLAVORS

Sauces form the foundation of Western cuisine, and stocks form the foundation of most sauces. Making a stock is all about extracting flavors and aromas from meat, seafood, vegetables, or some combination of these ingredients. Despite many recent high-tech advances in the kitchen, cooks have come up with few truly new methods to mine flavor from food since the early 20th century, when the iconic French chef Auguste Escoffier codified a stockmaking process that became the standard of haute cuisine.

For more on this history of Escoffier and the rise of Nouvelle Cuisine, see Evolution and Revolution, page 1·14.

In most contemporary kitchens, stocks remain as central to the food as they were in Escoffier's own kitchens, including the one at the Ritz Hotel, where he laid much of the groundwork for the classic dishes that would make French cuisine famous. Escoffier made sure that he appointed only the most talented staffer to be his saucier and stockmaker.

For a classic Escoffier veal stock, start the *mirepoix*—a versatile flavor base for many stocks, sauces, soups, stews, and the like—by coarsely chopping an appropriate amount of onions, carrots, and celery in a ratio of 2:1:1 (by weight). Next, select a portion of bones and meat that is about five times the volume of the *mirepoix* and cut the meat into 2.5 cm / 1 in cubes. After browning the veal bones and meat—often with tomato paste—place the ingredients into a big pot and add enough water to almost cover the mix, then cook at a simmer for a good part of a day or two. You can use variations on essentially the same procedure to make game stock, chicken stock, fish fumet, and vegetable stocks.

For more on making stocks, including formulas and step-by-step instructions, see page 297.

With a few good stocks as the foundation, classical French cuisine evolved a huge variety of sauces, both generic and special-purpose. Building upon the flavor base of a stock by adding a roux to thicken it, infusing it with herbs and spices, adding wine or vinegar reductions, and judiciously seasoning it created an elaborate hierarchy of classical sauces from just a few stocks.

Overthrowing the edifice of codified stocks and sauces was, in fact, one of the ways that chefs innovated during the rise of Nouvelle cuisine in the 1960s and 1970s. Rather than rely on stocks, Nouvelle cooks relied on intensely flavored pan juices, light herbal infusions, fresh vegetable and fruit juices, and coulis for sauces. Instead of being thickened with a stodgy and flavor-masking flour-based roux, Nouvelle sauces were thickened through evaporative reduction; bulking with a vegetable puree; or whisking in butter, cream, or oil to form a thickened emulsion. Those were useful contributions that continue to feature in kitchens today, but stocks never really went away. Unchanged in preparation, they remain fundamental to Western cooking.

Had he not retired in 1921, Escoffier, a great innovator in his day, might have taken interest in certain observations of the British biologist J.B.S. Haldane and perhaps even applied the scientist's fundamental insights to cooking. In Haldane's 1926 essay "On Being the Right Size," he noted that the ratio of an animal body's surface area to its volume has profound effects on the way it interacts with heat, pressure, and other natural forces.

"You can drop a mouse down a thousand-yard mine shaft; and, on arriving at the bottom, it gets a slight shock and walks away, provided that the ground is fairly soft," Haldane wrote. "A rat is killed, a man is broken, a horse splashes." Air resistance to movement, he continued, is directly proportional to an object's surface area. If you "divide an animal's length, breadth, and height each by ten; its weight is reduced to a thousandth, but its surface only to a hundredth." A high ratio of surface area to volume, in other words, can save a falling animal's life if air resistance, which goes in step with surface area, slows its descent enough.

That ratio has deep implications for the preparation of stocks as well, affecting not only their cooking time but also how completely flavor is extracted from the ingredients.

Hibiscus tea extraction

Size Matters

The fact that surface area and volume scale differently (as scientists say) explains why we grind coffee beans. To apply Haldane's reasoning, if you were to divide a roasted coffee bean by a factor of ten in each spatial dimension, you would get a thousand tiny coffee grounds, each having one-thousandth the volume and one-hundredth the area of the intact bean. The total volume of the 1,000 grounds equals that of a single bean. But if you add up the surface area of the particles, the sum is 100 times that of the original bean. Grinding the bean is therefore like installing a hundred extra little doors through which flavor can exit from the bean's once-inaccessible interior. And the more finely you grind the bean, the more total surface area emerges.

In 1855, the German physiologist Adolf Fick described **Fick's first law of diffusivity,** which more directly connects the science behind Haldane's observations to food. We all know from experience, for example, that when a bottle of perfume is opened, it takes a few minutes for the odor to reach the far corners of the room. Fick's first law postulates that matter (aromatic molecules) diffuses through a porous medium (air) from regions of high concentration to areas of lower concentration and that it does so at a rate that is proportional to the difference between the local concentration levels.

For more on how grinding affects coffee, see page 4·374.

Flavorful molecules diffuse in much the same way that heat does; in other words, just as energy moves more quickly from a flame to an ice cube than from a flame to a hot iron, sugar dissolves faster in unsweetened tea than it will in sweetened tea at the same temperature.

Fick's law also says something interesting about how extraction processes remove flavorful molecules from coffee particles, cubes of beef, or a *mirepoix*. The smaller the pieces of food used in a stock, the faster flavor chemicals migrate out of the food and into the stock. The difference in the speed of extraction depends roughly on the square of the smallest dimension of the pieces, so slicing food half as thick makes flavor extraction occur four times as fast.

Fick's law is closely related to the processes of heat transfer and of diffusion, which govern the flow of heat and water inside food as it cooks and dehydrates. Flavor molecules also leak out of meat or vegetables by diffusion, which is where the connection to Fick's law comes in.

When it comes to preparing stocks, Fick's law explains why the classic technique fails to finish the job: the pieces are just too big for much of the flavor inside to make its way out, even after simmering day and night. The proof is in a bite of what remains when you strain the beef, veal, chicken, fish, or vegetables from the stock at the end of the simmer. If it still tastes like beef, veal, chicken, fish, or vegetables, then the traditional process has not fully extracted all of the flavor.

After the first hour of simmering, in fact, most of the flavor that will ever come out of the meat and *mirepoix* already has. Even a two-day simmer cannot pull all of these key compounds from the interior regions of the pieces. This limitation explains the rationale for double stocks and triple stocks. Doubling a stock involves using the liquid stock from a first round of simmering as the "water" for a second round, in which the pot has been recharged with fresh batches of *mirepoix*. Another iteration still yields a further fortified triple stock. Double and triple stocks need little or no reduction, so although two or three times the quantity of ingredients is required, the final cost is about the same as that of normal stock that must be reduced to one-half or one-third its starting volume. Each repetition takes time, however, which is a precious commodity in any kitchen.

Although Fick's first law points to the problem of extracting flavor, it also suggests a simple solution: start out with much finer bits of meat and vegetables. As long as you can strain the pieces out at the end, the resulting stock can be as rich and clear as any you have ever made, but it can also be ready in a fraction of the typical time.

This approach involves slicing the vegetables thinly rather than leaving them in thicker chunks. You also cut the meat to, say, pea-sized pieces instead of thumb-sized cubes. Decrease the sizes of the ingredients enough, and you can slash the simmer time required by a factor of eight or more, from perhaps 16 hours to two. To go even further, grind the meat, then sweat or brown it to prevent the pieces from coalescing into large, sausage-like aggregations during cooking, which would nullify any gain from grinding. Most ingredients for savory stocks can be similarly manipulated to increase their surface area-to-volume ratios.

Time is not all you stand to save; rather than requiring, say, 10 kg / 22 lb of coarsely cut veal, you can get by with only 2.5 kg / 5.5 lb of browned ground veal to achieve the same intensity of flavor, and your pocketbook will thank you.

Pulling the flavor out of vegetables can be

SMALLER IS BETTER

Dicing stock ingredients more finely increases the surface area of the food dramatically without any change to its overall volume. Flavors will emerge much more readily from the finely diced mirepoix and meat, producing excellent stocks in less time and at lower expense.

a little tricky. One reason not to grind vegetables is that pulverizing plant matter releases juice, which changes the rates of flavor extraction so much that the traditional 2:1:1 ratio of vegetables no longer applies. Ground carrots, for instance, can leach too much sugar into the liquid. If you use ground vegetables, you must experiment to find a new set of proportions that give a balanced result. In most cases, it's best to simply cut the veggies into thin slices.

Extracted Under Pressure

The relentless cycles of evaporation and condensation that come with a long, slow simmer in a covered pan drive a wide range of chemical reactions that build complex flavors. So even though Fick's first law is sure to save ingredients, money, and time, you must be clever enough to apply the law without short-circuiting these reactions and compromising quality. To this end, thoughtful cooks have learned to leverage the effects of both temperature and pressure.

A good pressure cooker can thus be very handy when making stocks. These heavy pots with clamp-on lids and safety valves accelerate cooking because the boiling point of water rises with increasing pressure. When the gauge on your cooker indicates 1 bar / 15 psi of pressure above the liquid, the boiling point of the water inside can be as high as 120 °C / 248 °F. Increasing the temperature of the cooking stock by 20 °C / 36 °F forces both diffusion and the flavor reactions to run faster than they would in an open pot.

The liquid inside the pressure cooker will not boil, despite the elevated temperature, unless you let the heat get out of hand. A liquid boils when its vapor pressure exceeds the ambient pressure around it. Inside a sealed pressure cooker, as liquid water vaporizes, it raises the ambient pressure, which in turn increases the boiling point. So long as water vapor is not escaping the pressure cooker, the pressure inside will stay high enough to keep liquid water from boiling. Never reaching a boil is important because it keeps the stock clear. Turbulence from boiling emulsifies oils and small food particles from the ingredients into a stock, thereby making it murky.

A telltale sign that the stock is at a rolling boil inside a pressure cooker is a jet of steam or fog from the overextended pressure valve. This jet means that the pressure cooker is overpressurized, and for safety's sake the valve is relieving the excess pressure. But if the pressure is relieved, the stock itself will quickly come to a boil. Overpressurizing too often will ultimately damage the pot and lid; they won't seal properly, and the pressure cooker will be rendered useless.

When canning with pressure cookers, pressure canners, or autoclaves, it is essential to vent steam for about ten minutes before sealing the vessel.

A common problem with pressure cookers is using too much heat. This excess causes boiling in the pot and evaporation. It also can ruin the steam valve and the seal around the lid. Yet it does not make the temperature any higher.

For more on how to read a pressure gauge, see page 86.

The boiling point of water decreases with higher elevation and increases with higher pressure. For an explanation of these related phenomena, see page 86.

This venting purges air from the cooker or canner, leaving mostly water vapor. This step is necessary to reach the highest possible temperature for a given pressure (see chapter 7 on Traditional Cooking, page 2).

Unfortunately, at least for stockmaking, this step almost always seems to degrade the quality of the stock, a phenomenon that chefs Dave Arnold and Nils Norén have confirmed in experiments that include professional chefs as judges. The reasons for the quality decline are unclear, but most cooks who have tried it both ways generally prefer stock made in an unvented pressure cooker.

When the pressure-cooking step is done, you must let the cooker cool before removing the lid. That is a good safety tip, of course; a still-hot pressure cooker can spray hot liquid when opened. But that's not the only reason to do this. Cooling first means that volatile aromas in the vapor above the liquid will condense back into the liquid rather than escape into the kitchen. When you do remove the lid, you should be able to see all the way through a thin top layer of oil to the bed of spent meat and vegetable pieces at the bottom. The liquid in between should be beautifully clear.

Use flexible tubing to siphon the clear stock underlying the oil. This step minimizes any emulsification of fat from the top layer of the liquid into the stock that might otherwise occur.

Pressure-cooking is not only faster, it is also better because it creates more intense flavors than those produced by traditional simmering.

Pressure-cooking isn't how Escoffier made stock early in the last century, but we think it is how he would do it now.

We have found that blanching the bones and meat of chickens and other poultry before making the stock improves the flavor of the final product. The reasons why remain uncertain.

HOW TO Pressure-Cook Stock

Preparing stock with the mindset of a chemist as well as that of a cook will slash the required time and cost. Grind your meat and thinly slice your vegetables to extract more flavor in less time by exploiting Fick's law (see page 290), and use a pressure cooker to further accelerate the diffusion of flavors.

Take care not to let the pressure-cooker contents boil while the stock simmers. Boiling not only stresses the equipment but also causes turbulence that emulsifies fats and turns the stock cloudy. Despite the importance of venting a pressure cooker when canning, that can cause clouding when pressure-cooking a stock. Dave Arnold and Nils Norén at the French Culinary Institute in New York have also shown in experiments that the final product won't taste as good if the cooker is vented, perhaps because venting allows highly volatile (and desirable) flavor compounds to escape from the pot. Venting may also drive chemical reactions that produce unpleasant new flavors.

Operated correctly, a pressure cooker can yield stock that is nearly as clear as consommé. Solids sink to the bottom, a layer of oil rises to the top, and a thin layer of buoyant particles remains just below the oil.

1 **Prepare ingredients.** Grind meat and slice vegetables as thinly as possible; use ratios recommended in the table of Best Bets for Stocks on page 296. Roast bones or other sources of gelatin in oven. If desired, reserve 10% of raw ground meat to further clarify stock.

2 **Brown meat in fat directly in the cooker.** Oven-browning is also acceptable, but browning in the cooker produces a flavorful fond. Remove meat after it is browned. Be careful not to scorch the meat or the pot in the process.

3 **Add vegetables and cook until soft.** Deglaze the pot with any expressed juices. Remove vegetables. If needed, deglaze the pot further with water or another liquid.

4 **Combine all ingredients in pressure cooker.** Return browned meat and vegetables to the pot, then add liquids, roasted bones, optional aromatics, and optional reserved raw ground meat.

5 **Bring cooker to full pressure without venting.** If steam is jetting from the cooker, it is over-pressurized. Maintain pressure for time recommended in table on page 297.

6 **Remove from heat and cool until pressure abates (not shown).** You can accelerate cooling by running cold water over the pot.

7 **Skim off fat, then sieve stock gently.** Leave solids on bottom as you decant the stock from pot to sieve. Alternatively, if clarity is paramount, remove stock with a siphon. Or chill it to solidify fats, poke a hole through the fat, and pour out stock through hole.

2

3

4

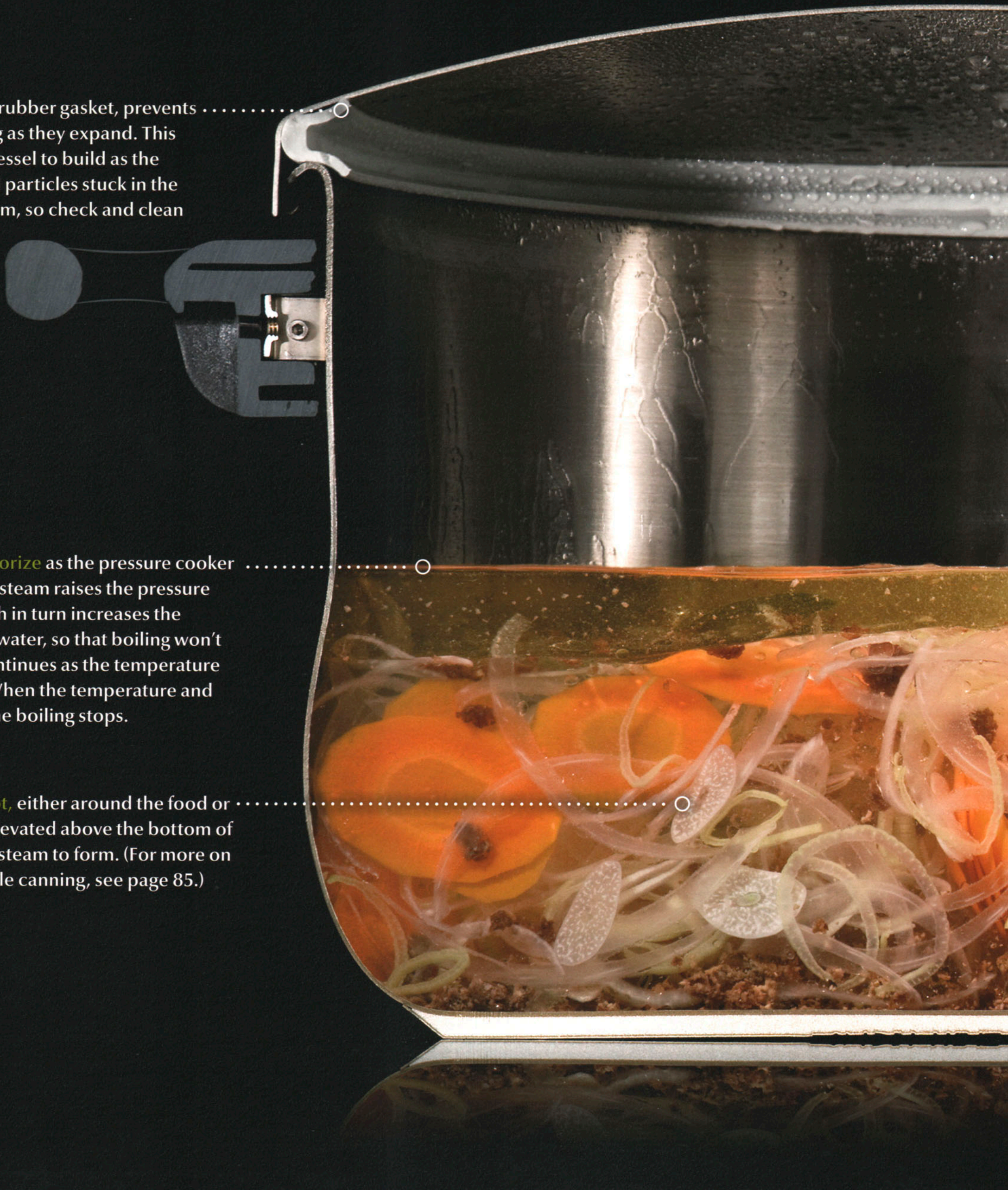
7

COOKING UNDER PRESSURE

Don't have two days to make your stock? A pressure cooker—essentially just a pot with a semi-sealed, lockable lid and a valve to control the pressure inside—can knock the cooking time down by as much as a factor of eight. The device works by using pressure to raise the boiling point of water, which normally limits the cooking temperature to 100 °C / 212 °F (at sea level; the temperature is lower at higher elevations). Because the effective cooking temperature is higher, the cooking time can drop substantially, particularly when combined with finely diced meat and thinly sliced vegetables.

Pressure cookers are efficient tools for other tasks, too. A bean stew that normally takes an hour to prepare might take just 15 minutes to cook under high pressure. That may explain why pressure cookers are particularly popular in India, where many dishes, such as daal, involve cooking lentils, dried beans, or other legumes to a smooth consistency—a time-consuming chore without a trusty pressure cooker.

Avoid overpressuring your pressure cooker, because over time this bends the flanges that hold the lid tightly on the pot; it will no longer pressurize.



The sealing ring, typically a rubber gasket, prevents steam and air from escaping as they expand. This causes the pressure in the vessel to build as the temperature rises. Any food particles stuck in the seal can cause it to leak steam, so check and clean the gasket regularly.

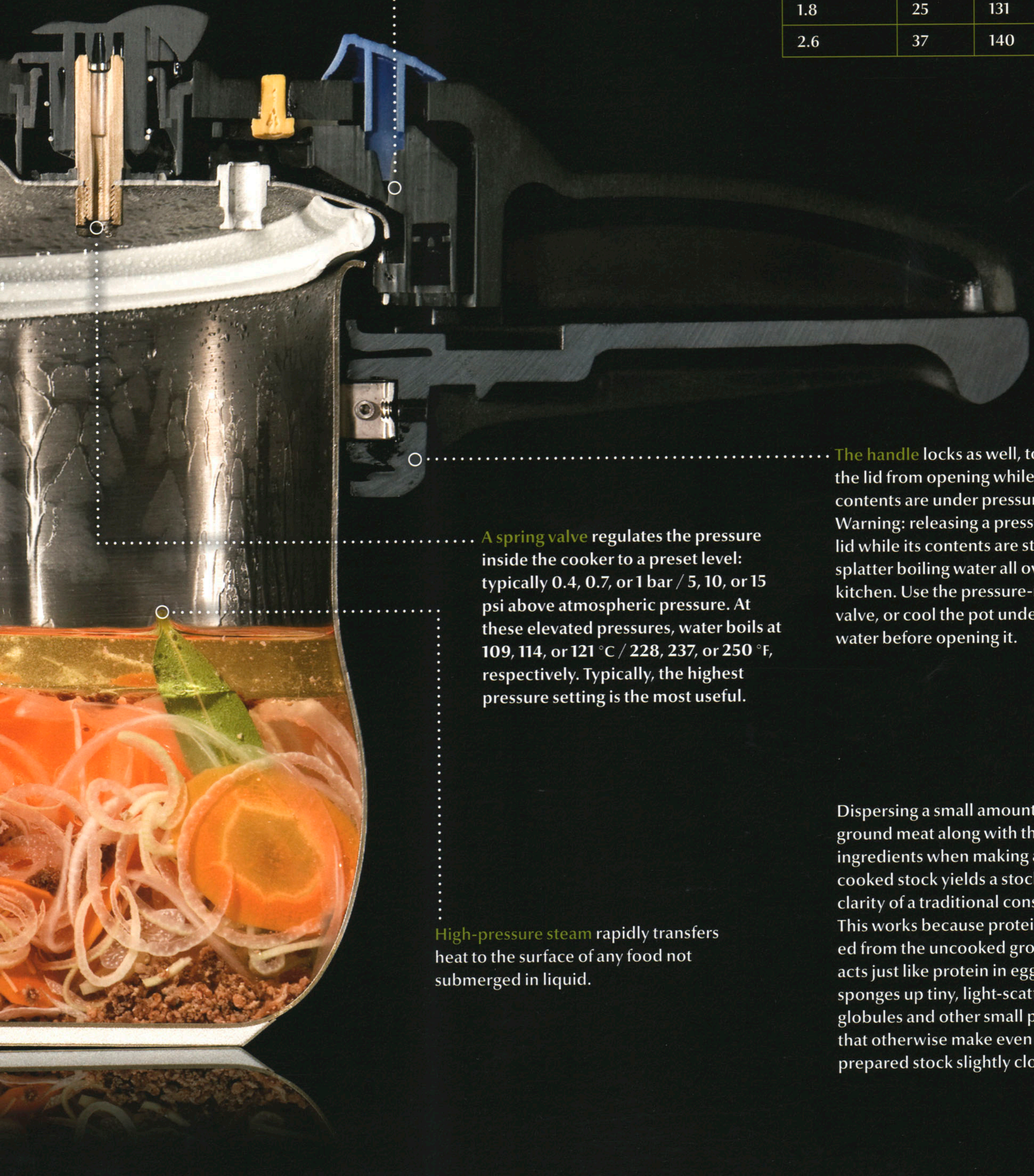
Water begins to vaporize as the pressure cooker heats. The resulting steam raises the pressure inside the pot, which in turn increases the boiling point of the water, so that boiling won't occur. This cycle continues as the temperature and pressure rise. When the temperature and pressure level off, the boiling stops.

Add enough water to the pot, either around the food or under a container of food elevated above the bottom of the pot, to enable plenty of steam to form. (For more on using a pressure cooker while canning, see page 85.)

Boiling Under Pressure

By adjusting the pressure inside a pressure cooker or autoclave, you can control the temperature that water reaches before it boils into steam.

Gauge pressure (above atmospheric)		Boiling point of water	
(bar)	(psi)	(°C)	(°F)
0.0	0	100	212
0.5	7	112	224
1.0	15	120	248
1.8	25	131	268
2.6	37	140	284



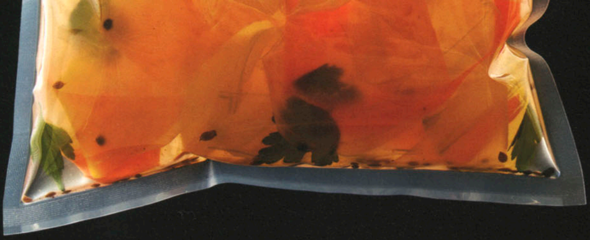
The lid locks with a bayonet-style mechanism that cinches against the sides of the cooker. The mechanism can be damaged from frequent overpressurization, rendering the cooker useless. Other designs use bolts that clamp around the outside.

The handle locks as well, to prevent the lid from opening while the contents are under pressure. Warning: releasing a pressure cooker lid while its contents are still hot can splatter boiling water all over the kitchen. Use the pressure-release valve, or cool the pot under running water before opening it.

A spring valve regulates the pressure inside the cooker to a preset level: typically 0.4, 0.7, or 1 bar / 5, 10, or 15 psi above atmospheric pressure. At these elevated pressures, water boils at 109, 114, or 121 °C / 228, 237, or 250 °F, respectively. Typically, the highest pressure setting is the most useful.

High-pressure steam rapidly transfers heat to the surface of any food not submerged in liquid.

Dispersing a small amount of raw ground meat along with the other ingredients when making a pressure-cooked stock yields a stock with the clarity of a traditional consommé. This works because protein extracted from the uncooked ground meat acts just like protein in egg white: it sponges up tiny, light-scattering fat globules and other small particles that otherwise make even a carefully prepared stock slightly cloudy.



PARAMETRIC RECIPE

STOCKS

Right after ingredient quality, stocks are perhaps the most important building block of a gourmet kitchen. The step in culinary evolution from plain water to flavorful infusions of meat or seafood, bones, vegetables, and herbs as the starting point for cooking was an inflection point in Western cuisine. In creating original, flavorful stocks that could be reduced into complicated sauces, chefs freed themselves from a reliance on pan drippings or jus. The systematic exploration and refinement of stocks led to the codification of sauces, which many consider to be the foundation of classic French cuisine (see page 1·9).

In many ways, the present age of experimentation mirrors that influential era. Today's culinary pioneers still value classical stocks, but they are also embracing new ingredients, culinary ideas from around the world, and modern cooking techniques like sous vide, pressure-cooking, and ultrasonic baths. Cooking stocks in a closed environment holds evaporation to a minimum, so more flavors remain in the broth.

Stocks and broths are both essential ingredients, but they are not the same. Stocks are unseasoned and never stand alone. Broths are finished, well-seasoned components.

Best Bets for Stocks

Stock	Fat	(scaling)	Bone	(scaling)	Meat	(scaling)	Liquid	(scaling)
chicken, duck, or pigeon	frying oil	8%	wings	40%	ground chicken	75%	water	100%
beef	suet	5%	calf's foot, split	20%	ground beef	80%	water red wine*	100% 10%
veal	frying oil	5%	veal knuckle	50%	ground veal	25%	water Madeira	100% 15%
lamb	frying oil	5%	lamb shoulder and neck	35%	ground lamb	100%	water	100%
pork	frying oil	7.5%	pork ribs	50%	ground pork	50%	water white port (dry)	100% 8%
shellfish	clarified unsalted butter	5%	lobster, shrimp, or crab shells and heads	65%	squid or scallop meat (optional)	20%	water dry vermouth	100% 15%
vegetable	vegetable oil	5%	n/a		n/a		water	100%
fish	olive oil	10%	fish bones	100%	n/a		water white wine	100% 10%
Chinese banquet			pork ribs duck wings chicken wings	20% 20% 15%	cured ham, thinly sliced	10%	water Shaoxing wine	100% 5%
Chinese everyday			chicken carcass	30%	ground pork	40%	water	100%
Japanese			chicken carcass chicken feet pork trotter	24% 6% 12%	ground pork shoulder	8%	water	100%
Thai			chicken wings pork ribs	20% 12%	ground pork	35%	water coconut water	100% 40%

*(*for brown stock only*)

MAKING BASIC STOCK

1 **Weigh cold water.** Scale all other ingredients relative to the water weight. For every 1 kg of water, for example, use 200 g of chicken wings and 750 g of ground chicken meat for chicken stock. Although the amount of water used is the biggest factor in the yield, the moisture of the ingredients used, the cooking time, and the cooking method all affect the yield.

2 **Mix vegetables and aromatics.** See Best Bets for Stock Aromatics on the next page for our recommendations.

3 **Add stock ingredients and water.** See the Best Bets for Stocks table below for our recommendations.

4 **Cook.** The table lists suggested cooking methods, times, and temperatures. If pressure-cooking, set the pressure shown on the gauge to 1 bar / 15 psi.

5 **Rest until pressure cooker has depressurized, about 20 min.** Strain.

Preparation (brown stock only)	(h)	Cook	(h)	(°C)	(°F)
roast meat and bones	½	pressure-cook	1½	n/a	n/a
roast meat and bones	1	pressure-cook	2½	n/a	n/a
roast meat	¾	pressure-cook	2½	n/a	n/a
roast meat	1	pressure-cook	1½	n/a	n/a
roast meat and bones	1	pressure-cook	2	n/a	n/a
fry shells with tomato paste until golden brown	10 min	cook sous vide	¾	88	190
sauté sliced vegetables until golden brown	1	cook sous vide	3	85	185
roast bones	20 min	cook sous vide	1¼	88	190
		pressure-cook	2	n/a	n/a
		pressure-cook	1¼	n/a	n/a
		cook sous vide	1¼	90	194
		pressure-cook	1½	n/a	n/a

VARIATION: White Stock

1 **Follow steps 1 and 2 in Making Basic Stock, above.**

2a **Blanch bones.** Cover the bones in cold water, and bring to a boil.

2b **Sweat stock ingredients and aromatics in fat.** See the Best Bets for Stocks table below for recommended ingredients.

2c **Follow steps 3–5 in Making Basic Stock.**

VARIATION: Shellfish Stock

1 **Follow steps 1 and 2 in Making Basic Stock, above.**

2a **Sauté shellfish, aromatics, and tomato paste in fat on stove top.** See the table at left for recommended ingredients.

2b **Follow steps 3–5 in Making Basic Stock, above.**

VARIATION: Rich Brown Stock

1 **Weigh water.**

2a **Roast meat, bones, and vegetables.** Cook at 190 °C / 375 °F for the time indicated in the table at left. Add tomato paste if desired.

2b **Deglaze roasting pan.** Use wine or water.

2c **Combine aromatics with roasted ingredients.**

2d **Follow steps 3–5 in Making Basic Stock, above.**

Cooked stocks must be used immediately or chilled quickly to prevent bacteria growth. For more on safe preparation of stocks, see page 1·206.

Best Bets for Stock Aromatics

Aromatic ingredients provide flavor and aroma notes to complement the base stocks. The variations below are some typical combinations that we like.

Stock	Vegetable	(scaling)*	Herb	(scaling)*	Spice	(scaling)*
vegetable	onion	33%	parsley	0.75%	black peppercorns	0.1%
	carrot	25%	bay leaf	0.01%	coriander seed	0.2%
	leek	8%	thyme	0.10%	star anise	0.2%
	tomato, peeled and seeded	8%	chive	1.00%		
	celery	5%				
	mushroom	5%				
poultry	onion	6%	parsley	0.50%	black peppercorns	0.1%
	carrot	5%			garlic	1%
	leek	5%				
meat, beef	onion	10%	thyme	0.8%	star anise	0.05%
	carrot	10%	rosemary	0.15%	garlic	1%
	celery	2%				
	tomato paste (for brown stock)	5%				
game, lamb	onion	7%	bay leaf	0.01%	star anise	1.5%
	carrot	7%	thyme	1.00%	garlic	2%
	celery	2%	sage	0.20%	black peppercorns	0.2%
shellfish	carrot	5%	parsley	0.25%	fennel seed	0.01%
	onion	5%	thyme	0.10%	saffron	0.005%
	leek	2%	basil	0.20%		
	fennel	2%				
	button mushroom	2%				
	tomato paste (for brown stock)	5%				
fish	carrot	33%	n/a		garlic	2%
	onion	26%			coriander seed	0.3%
	leek	13%			star anise	0.2%
	fennel	13%				
	tomato paste (for brown stock)	5%				
Chinese banquet	scallion	0.2%	n/a		ginger	0.4%
					white peppercorns	0.01%
					cinnamon sticks	0.05%
Chinese everyday	scallion	1.2%	n/a		ginger	1%
Japanese	onion	3.5%	n/a		ginger	0.4%
	carrot	3.5%			garlic	0.75%
	scallion	1%			kombu	0.1%
					bonito flakes	5%
Thai	scallion	1%	cilantro stalks	0.20%	ginger	0.4%
	cabbage	1%	Thai basil	0.30%	garlic	0.5%
	fried shallot	4%	makrud lime leaf	0.40%		

*(*set weight of water to 100%*)

THE SCIENCE OF

Determining What Tastes Best

Detecting a difference and measuring a preference are harder than you might think. Cognitive scientists have shown that human perception is naturally biased by the order in which the alternatives are tasted. So unless you follow a tasting protocol that compensates for these biases, you could easily fool yourself into thinking that some subtle addition makes a real difference when it actually doesn't—or even that an addition was a mistake when actually it was an improvement.

Detecting a real difference requires a triangle tasting test of three samples; see How to Set Up a Triangle Test, page 4·336. When we were comparing stock recipes and stockmaking methods, we measured our preferences by using a slightly more complex procedure with four samples—sometimes called a ranking test.

It's important to designate some independent person who does not take part in the ranking to set up the preference test and record and analyze the results. Let's call that person the investigator. It's also important to make the dishes or drinks as similar to one another in appearance as possible.

Each test participant, or taster, always tastes four samples, but among those four tastes only two or three are actually distinct. For example, a taster will either receive two samples of recipe A and two of recipe B, or will taste two As, one B, and one C. At least one recipe is always presented twice to each participant. The more tasters, the more statistically meaningful the results will be.

The test must be blind, meaning participants cannot know which sample is which; that is why the samples must look alike (or the participants must be blindfolded). The investigator chooses code names for each sample and keeps secret the key that explains which code name corresponds to which sample. Use a meaningless descriptor—like red, green, orange, and blue—rather than numbers or letters that, because of their inherent order, may elicit a biased reaction.

After the investigator decodes the rankings of the tasters, a real preference will be revealed if the sample that was presented twice appears consistently in the top, middle, or bottom of the rankings: for example AABC, BAAC, or CBAA. If the duplicated sample is instead split—say, BACA—you must conclude that none of the recipes is perceptibly better than the others.

Preference testing helps when you must decide whether a time-consuming or expensive step is worthwhile. For example, we wondered whether we could skip the blanching step when making white stocks. Side-by-side comparison or a triangle test may have illustrated the flavor differences, but it required a preference tasting to show that our cooks agreed that white stocks made with blanched ingredients are genuinely better than those made without blanching.

1. **Prepare and label the samples.** An "investigator" who does not take part in the tasting should divide two or three recipes into four tasting samples, then label the samples with meaningless code names. Use the table above to make a secret key, seen only by the investigator, that records how the recipes correspond to the code names.

2. **Present the samples in a different order to each taster.** Each taster should get at least one of the sample presented twice. If it is not possible to make the recipes visually indistinguishable from one another, blindfold the tasters before presenting the samples.

3. **Have tasters rank their preferences.** Allow participants to taste the samples as many times as they like.

4. **Decode and analyze the results.** If there is a meaningful preference, the two instances of the sample presented will fall adjacent to one another somewhere in the ranking.

It is shocking how easy it is to fool yourself if you try to taste things without a formal preference test. Human perception seems great but, as optical illusions show us, we are not as perfect as we think.

BROWN VEAL STOCK

Yields 650 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Veal knuckle and neck bones, sawed into 5 cm / 2 in pieces, if possible	500 g	50%	① Cover with water. ② Bring to a boil, skimming often. ③ Drain, discarding water.
Neutral oil	75 g	7.5%	④ Coat bones with oil. ⑤ Roast in 190 °C / 375 °F oven until golden brown, about 30 min. ⑥ Reserve bones, and discard excess oil.
Veal trimmings, finely ground	500 g	50%	⑦ Combine on nonstick baking sheet. ⑧ Roast in 190 °C / 375 °F oven until evenly brown, about 20 min. ⑨ Strain, and reserve meat.
Neutral oil	50 g	5%	
Unsalted butter	15 g	1.5%	⑩ Melt butter in pressure cooker. ⑪ Add vegetables to pressure cooker. ⑫ Cook uncovered, stirring frequently, until moisture has evaporated and vegetables are tender, about 7 min.
Sweet onions, peeled and thinly sliced	50 g	5%	
Carrots, peeled and thinly sliced	25 g	2.5%	
Leek, thinly sliced	25 g	2.5%	
Tomato confit see page 5·62	40 g	4%	⑬ Add to pressure cooker, and increase heat to high. ⑭ Sauté vegetables and confit uncovered, stirring constantly until brown, about 4 min.
Water	1 kg	100%	⑮ Add to pressure cooker with bones and meat. ⑯ Pressure-cook mixture at a gauge pressure of 1 bar / 15 psi for 2½ h. ⑰ Cool. ⑱ Strain. ⑲ Vacuum seal and refrigerate until use.
Vodka	20 g	2%	
Parsley leaves	3 g	0.3%	
Black peppercorns, crushed	1 g	0.1%	

(2009)

EXAMPLE RECIPE

PRESSURE-COOKED WHITE CHICKEN STOCK

Yields 400 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Chicken wing meat and bones, chopped	350 g	70%	① Cover with cold water. ② Bring to a boil, then drain chicken immediately.
Water	500 g	100%	③ Combine with blanched chicken in pressure cooker. ④ Pressure-cook at a gauge pressure of 1 bar / 15 psi for 1½ h. ⑤ Strain through fine sieve. ⑥ Cool. ⑦ Vacuum seal, and refrigerate until use.
Chicken thigh meat, finely ground	350 g	70%	
Sweet onions, peeled and thinly sliced	50 g	10%	
Carrots, peeled and thinly sliced	25 g	5%	
Leeks, thinly sliced	25 g	5%	
Garlic, thinly sliced	5 g	1%	
Parsley leaves and stems	1 g	0.2%	
Black peppercorns	0.5 g	0.1%	

(2008)

EXAMPLE RECIPE

BROWN BEEF STOCK

Yields 650 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Beef chuck, finely ground	200 g	40%	① Vacuum seal. ② Cook sous vide in 90 °C / 194 °F bath until juices are released, about 1 h. ③ Strain, reserving juice; discard meat. ④ Cool beef juice, and reserve.
Oxtail, thinly sliced on a band saw	500 g	100%	⑤ Roast oxtail with suet in 190 °C / 375 °F oven until oxtail is brown, about 30 min. ⑥ Discard excess fat. ⑦ Cool, and reserve.
Rendered beef suet	75 g	15%	
Water	500 g	100%	⑧ Combine in pressure cooker with beef juice and oxtail. ⑨ Pressure-cook at a gauge pressure of 1 bar / 15 psi for 2½ h. ⑩ Strain. ⑪ Cool. ⑫ Vacuum seal, and refrigerate until use.
Red wine (full-bodied)	100 g	10%	
Carrots, peeled and thinly sliced	50 g	10%	
Yellow onions, peeled and thinly sliced	50 g	10%	
Celery, peeled and thinly sliced	20 g	4%	
Leeks, whites only, thinly sliced	20 g	4%	
Red port (dry)	20 g	4%	
Parsley leaves	10 g	2%	
Thyme	1 g	0.2%	
Bay leaf	0.5 g	0.1%	

(2009)

HOW TO Make Stock Sous Vide

For many vegetable and seafood stocks, extraction at low temperature yields a better flavor than high-temperature pressure-cooking does. In such cases, prepare the stock sous vide, which minimizes turbulence while accurately controlling the temperature for hours at a time.

If you have an ultrasonic bath (below), we highly recommend combining sous vide cooking with ultrasonic treatment. The high-frequency vibrations accelerate extraction and yield a stock with fuller flavor. The vibrations do unfortunately cloud the stock slightly. Filtering or using a centrifuge can improve the clarity (see page 351).

1 **Prepare ingredients.** Grind meat finely, and slice vegetables thinly. Use ratios recommended in the table of Best Bets for Stocks on page 296. Roast bones.

2 **Vacuum seal ingredients together.**

3 **Cook sous vide in 85 °C / 185 °F bath for 3 h.**

4 **Cavitate in ultrasonic cleaning bath for 30 min (optional).** If the ultrasonic bath has a temperature setting, put it at the highest degree available, typically 60 °C / 140 °F.

5 **Refrigerate for 12 h, then strain.**

6 **Vacuum seal again, and refrigerate or freeze until needed.**

EXAMPLE RECIPE

SOUS VIDE FISH STOCK

Yields 1.5 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Fish bones, cleaned and rinsed	2 kg	133%	① Panfry bones until golden.
Neutral oil	50 g	3%	
Vermouth	350 g	23%	② Deglaze bones.
White wine (dry)	200 g	13%	③ Cool mixture completely, and reserve.
Carrots, peeled and thinly sliced	500 g	33%	④ Prepare vegetables as noted.
Onions, peeled and thinly sliced	400 g	27%	⑤ Combine, and cook until soft.
Fennel, thinly sliced	200 g	13%	⑥ Cool completely.
Leeks, thinly sliced	200 g	13%	
Garlic cloves, thinly sliced	30 g	2%	
Neutral oil	20 g	1.5%	
Water	1.5 kg	100%	⑦ Combine with bones and vegetables.
Coriander seeds	5 g	0.3%	⑧ Vacuum seal.
Star anise	2.5 g	0.17%	⑨ Cook sous vide in **80** °C / **176** °F bath for 1¼ h.
			⑩ Strain.
			⑪ Cool.
			⑫ Vacuum seal, and refrigerate until use.

(2010)

EXAMPLE RECIPE

SOUS VIDE VEGETABLE STOCK

Yields 350 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Water	500 g	100%	① Prepare vegetables as noted.
Onions, peeled and thinly sliced	280 g	56%	② Combine. ③ Vacuum seal.
Carrots, peeled and thinly sliced	200 g	40%	④ Cook sous vide in **85** °C / **185** °F bath for 3 h.
Celery, peeled and thinly sliced	100 g	20%	⑤ Transfer to ultrasonic cleaning bath, and cavitate for 30 min to improve extraction. If unavailable, proceed with remaining steps.
Leeks, whites only, thinly sliced	100 g	20%	⑥ Cool, and refrigerate for 12 h.
Button mushrooms, thinly sliced	50 g	10%	⑦ Strain.
Tomatoes, peeled, seeded, and chopped	50 g	10%	⑧ Vacuum seal, and refrigerate until use.
Chives	10 g	2%	
Parsley	10 g	2%	
Coriander seeds	1.5 g	0.3%	
Black peppercorns	1 g	0.2%	
Thyme	1 g	0.2%	
Bay leaf	0.5 g	0.1%	
Star anise	0.5 g	0.1%	

(2010)

PARAMETRIC RECIPE

BROTH

Broths—*bouillons* in French—are fully seasoned soups and are thus different from unseasoned stocks. People sometimes use the term broth to connote something frail or paltry, but a broth is hardly weak. In many ways, broths are the very essence of food, nourishment, and flavor, and they are integral components in any gourmet kitchen.

No soup is made without a broth, and no cuisine is complete without soups. Broth can be quite simple or refined and even fancy. It can be clear or cloudy, rich or light. A good broth will stand alone, but some broths—especially those made from ham or game—are more often used to boost the flavor and intrigue of traditional dishes without adding greatly to the mass.

The classic image of broth cooking is an open kettle or cauldron, but as with stocks, we prefer the quality of broths cooked sous vide or in a pressure cooker.

Broths are usually more strongly flavored than stocks because stocks are basic building blocks and thus might be reduced or combined with other things to make a final sauce or other dish. In contrast, broths *are* the final dish, so they need to have full flavor.

In the table below we have shown broths made from stocks, but, by combining the formulas, you could combine making broth and stockmaking into a single cooking step.

For more on seasoning broths, see Acidifiers, page 314, and Best Bets for Adding Flavor with Alcohol, page 317.

MAKING A BROTH

1. **Select a broth from the table.**
2. **Prepare and scale the liquid, meat, vegetables, and aromatics.** Weights in the table are proportional to the liquid scaled to 100%. For example, to make dashi, for every 100 g of water used, add 5.2 g of bonito flakes and 2.5 g of kombu.
3. **Pressure-cook (set to 1 bar/15 psi), or vacuum seal and cook sous vide.** Recommended cooking methods, temperatures, and times are given in the table.
4. **Sieve.**

When making dashi, the bonito flakes are added only after the kombu has been cooked sous vide.

Best Bets for Broths

Broth	Stock	(scaling)	Meat	(scaling)
pot-au-feu	white beef stock* vegetable stock* madeira	100% 50% 4%	oxtail, chopped short rib meat, ground	30% 20%
ham broth	water madeira fino sherry	100% 25% 19%	prosciutto, thinly sliced ham, thinly sliced Ibérico ham, thinly sliced	62.5% 25% 25%
game broth	brown chicken stock* gin red wine	100% 10% 10%	venison, ground, roasted pigeon wings, roasted pheasant trimmings, blanched	50% 12% 10
capon broth	white chicken stock* white wine (dry)	100% 25%	capon meat, ground	30%
salt cod broth	water	100%	salt cod skins, soaked for 12 h in cold water	20%
dashi	water	100%	bonito flakes	5.2%
pho broth	water	100%	beef knuckles, roasted	44%
Chinese ginger soy fish broth	Chinese fish stock** Shaoxing wine light soy sauce	100% 1.5% 1.5%	n/a	n/a
"Marmite broth" adapted from Heston Blumenthal	red wine water	750%** 100%	n/a	n/a

*(*see page 296*) **(*reduced to 250%*)

Vegetable	(scaling)	Aromatic	(scaling)	Cook				See page
				Method	(h)	(°C)	(°F)	
carrot turnip, thinly sliced onion, thinly sliced	10% 10% 8%	clove bay leaf	0.01% 0.05%	pressure-cook	2	n/a	n/a	
shallot, thinly sliced garlic, thinly sliced	25% 12.5%	black pepper sherry vinegar	2.50% to taste	pressure-cook	1½	n/a	n/a	next page
whole onion carrot, thinly sliced celery, thinly sliced	5% 5% 2%	juniper berries, crushed sage, thinly sliced	0.2% 0.1%	pressure-cook	1	n/a	n/a	3·100
shallot, thinly sliced	15%	Parmesan, grated cinnamon extract (see page 326) sage, thinly sliced	10% 3% 0.15%	cook sous vide	2	88	192	
onion, thinly sliced garlic, thinly sliced	20% 10%	thyme	0.2%	cook sous vide	3	90	196	
kombu	2.5%	n/a		cook sous vide	1	60	140	next page, 4·94
whole onion, charred ginger, charred	24% 5%	black pepper star anise cinnamon allspice	0.04% 0.02% 0.02% 0.01%	pressure-cook	1½	n/a	n/a	307
scallion ginger chili	3% 2% 0.05%	Szechuan pepper rice vinegar honey	0.05% to taste to taste	cook sous vide	35 min	80	176	
leek, thinly sliced carrot, thinly sliced onion, thinly sliced	1,000% 500% 1,000%	black pepper Marmite sherry vinegar	to taste to taste to taste	cook sous vide	45 min	80	176	

EXAMPLE RECIPE

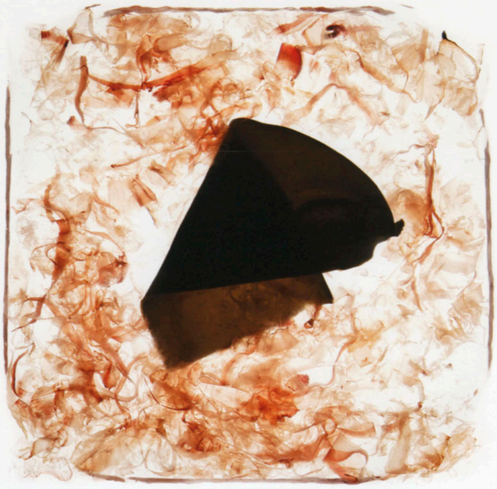
HON DASHI ADAPTED FROM YOSHIHIRO MURATA

Yields 360 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Water	475 g	100%	① Vacuum seal together.
Rishiri kombu, or best quality seaweed available (brown kelp)	12 g	2.5%	② Cook sous vide at **60** °C / **140** °F for 1 h.
			③ Cool, and refrigerate for 2 h.
			④ Strain.
Bonito flakes (katsuobushi)	25 g	5.3%	⑤ Heat broth to **85** °C / **185** °F.
			⑥ Add bonito flakes, and steep for 10 s.
			⑦ Strain.
			⑧ Cool.
			⑨ Vacuum seal, and refrigerate until needed.

(original 2010, adapted 2010)

The kombu flavor can be increased by extending the refrigerator time from 2 h to as long as 12 h. The longer the time, the stronger the flavor.



EXAMPLE RECIPE

HAM BROTH

Yields 535 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Water	500 g	100%	① Prepare ingredients as noted.
Prosciutto ends, thinly sliced	250 g	50%	② Combine in pressure cooker.
Cooked white ham, thinly sliced	100 g	20%	③ Pressure-cook at a gauge pressure of 1 bar / 15 psi for 1½ h.
Jamón Ibérico, thinly sliced	100 g	20%	④ Strain.
Madeira	100 g	20%	⑤ Cool completely.
Shallots, thinly sliced	100 g	20%	⑥ Measure 500 g.
Fino sherry	75 g	15%	
Garlic, thinly sliced	50 g	10%	
Black peppercorns, crushed	10 g	2%	
Ham broth, from above	500 g	100%	⑦ Disperse gelatin and gum in cold broth.
160 Bloom gelatin	4 g	0.8%	⑧ Heat broth just enough to dissolve gelatin.
Xanthan gum	0.75 g	0.15%	
Salt	to taste		⑨ Season, and cool.
Sherry vinegar	to taste		⑩ Vacuum seal, and refrigerate until needed.

(2010)

Any cured meat can be used here instead of ham.

EXAMPLE RECIPE

OXTAIL PHO BROTH

Yields 4.75 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Black peppercorns	2 g	0.04%	① Combine.
Cinnamon stick	1 g	0.02%	② Toast spice mix.
Star anise, ground	1 g	0.02%	③ Place in sachet made of cheesecloth.
Allspice	0.5 g	0.01%	
Water	5 kg	100%	④ Combine in pressure cooker.
Beef knuckles, blanched	2.2 kg	44%	⑤ Add sachet.
White onions, whole, unpeeled, and charred	1.2 kg	24%	⑥ Pressure-cook broth at a gauge pressure of 1 bar / 15 psi for 3 h.
Oxtail, jointed and seared	900 g	18%	⑦ Discard sachet.
Ginger, halved and charred	250 g	5%	
Fish sauce	to taste		⑧ Season, and cool.
Salt	to taste		⑨ Vacuum seal, and refrigerate until needed.
Sugar	to taste		

(original 2003, adapted 2010)

The sachet is a pouch made of cheesecloth that keeps the spice mixture together in much the same way that a tea bag holds tea leaves. The broth can be made without the sachet, but then you will have to filter out the loose spice mix to get a perfectly clear broth.

EXAMPLE RECIPE

LAKSA BROTH

Yields 500 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Onions, peeled and chopped	100 g	28%	① Prepare ingredients as noted.
Lemongrass, finely minced	40 g	11%	② Blend together in food processor.
Candlenuts, roasted and grated	30 g	8.3%	③ Measure 28 g of paste, reserving the rest.
Shrimp paste	20 g	5.5%	
Dried chili	5 g	1.4%	
Galangal, peeled and chopped	5 g	1.4%	
Turmeric (fresh), peeled and chopped	0.7 g	0.2%	
Laksa paste, from above	28 g	7.8%	④ Sauté until golden and very fragrant, about 3 min.
Neutral oil	20 g	5.5%	
White fish stock see page 303	360 g	100%	⑤ Transfer paste to large pot, and whisk in stock and cream.
Caramelized coconut cream see page 4-50	100 g	28%	⑥ Simmer broth for 5 min.
Fish sauce	to taste		⑦ Season, and cool.
Lime juice	to taste		⑧ Vacuum seal, and refrigerate until needed.

(2010)

Laksa is one of the great dishes of the Peranakan culture that merges Chinese and Malay traditions. Many feel that the best laksa is found in the food-hawking centers of Singapore.

EXAMPLE RECIPE

BOUILLABAISSE BROTH

Yields 750 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Tomatoes, peeled, seeded, and diced	120 g	13%	① Prepare vegetables as noted. ② Combine.
White onions, thinly sliced	115 g	13%	③ Cook over low heat until tender and golden, about 25 min.
Fennel, thinly sliced	100 g	11%	
Shallots, thinly sliced	85 g	9.5%	
Leeks, thinly sliced	80 g	9%	
Carrots, thinly sliced	75 g	8%	
Olive oil	50 g	5.5%	
Garlic, thinly sliced	25 g	3%	
Tomato confit, pureed (or tomato paste) see page 5·62	60 g	7%	④ Add, and increase heat to medium high. ⑤ Sauté until browned, about 5 min, and reserve.
Fish bones and head	800 g	89%	⑥ Coat bones in oil.
Neutral oil	75 g	8%	⑦ Bake in **180** °C / **325** °F oven until golden, about 45 min.
			⑧ Cool.
Water	900 g	100%	⑨ Combine with vegetable mixture and fish parts.
White wine (dry)	200 g	22%	
Pastis	50 g	5.5%	⑩ Vacuum seal.
Thyme	3 g	0.33%	⑪ Cook sous vide in **80** °C / **175** °F bath for 1¼ h.
Black peppercorns, crushed	1 g	0.1%	
Bay leaf	0.6 g	0.06%	⑫ Strain.
Saffron threads	0.3 g	0.003%	⑬ Cool.
			⑭ Skim fat from surface.
Blood orange juice	17 g	2%	⑮ Season.
Red miso paste	13 g	1.4%	⑯ Cool.
Blood orange zest, finely grated	1 g	0.1%	⑰ Vacuum seal, and refrigerate until needed.
Salt	to taste		

(2010)

Bouillabaisse is the classic fisherman's stew hailing from Marseilles and the surrounding region. Originally prepared as an all-in-one stew, we think it is much better to cook the broth and the fish components separately; otherwise the fish will be overcooked. The broth can also be served alone.

Bouillabaisse is a classic example of a regional food that has developed a cult following. Whenever this happens, one sees similar phenomena: fierce arguments about which versions are most authentic or best, and equally heated controversy as to where the dish originated. People often insist on keeping their recipes secret. Cassoulet (see page 5·81) is another cult food from a different region of France. Chili has a similar following in Texas and other parts of the American Southwest.

EXAMPLE RECIPE

BACON DASHI INSPIRED BY DAVID CHANG

Yields 800 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Water	1 kg	100%	① Vacuum seal together.
Kombu	25 g	2.5%	② Cook sous vide in **60** °C / **140** °F bath for 1 h.
			③ Strain out kombu.
Bacon, thinly sliced	250 g	25%	④ Vacuum seal with kombu-infused water.
Sake (dry), flamed off	30 g	3%	⑤ Cook sous vide in **85** °C / **185** °F bath for 1½ h.
			⑥ Strain out bacon.
Mirin	10 g	1%	⑦ Combine.
Soy sauce	10 g	1%	⑧ Adjust seasoning as needed.
Sake	6 g	0.6%	
Sugar	1.4 g	0.14%	

(2010)

The quality of the bacon used determines the quality of the final dashi.

EXAMPLE RECIPE

TOM YUM BROTH

Yields 750 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Shallots, chopped	160 g	32%	① Prepare ingredients as noted.
Lemongrass, bruised and sliced thinly	78 g	15.6%	② Combine in blender. ③ Puree.
Palm sugar	60 g	12%	④ Measure 100 g of paste.
Tamarind paste	60 g	12%	
Garlic, chopped	50 g	10%	
Ginger, peeled and cut into coin shapes	45 g	9%	
Cilantro stems, washed and chopped	40 g	8%	
Galangal, peeled and chopped	40 g	8%	
Belacan shrimp paste	10 g	2%	
Makrud (kaffir) lime leaf, bruised	8 g	1.6%	
Bird's Thai chili, chopped	5 g	1%	
Neutral oil	as needed		⑤ Sauté paste until dry and very fragrant, about 5 min.
Shrimp stock (or vegetable stock) see page 296	500 g	100%	⑥ Whisk into sautéed paste in large pot, and bring to a simmer.
Palm sugar	20 g	4%	⑦ Season.
Fish sauce	7 g	1.4%	⑧ Cool.
Salt	2 g	0.4%	⑨ Vacuum seal, and refrigerate until needed.
Lime juice	to taste		

(2010)

Like many Asian broths, the taste of Tom Yum derives largely from a flavorful paste.

EXAMPLE RECIPE

BAKED POTATO BROTH

Yields 300 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Russet potato skins	100 g	100%	① Coat skins with oil.
Frying oil	20 g	20%	② Bake in 95 °C / 200 °F oven for 7 h, until golden and completely desiccated. ③ Cool.
Russet potatoes, peeled and thinly sliced	75 g	75%	④ Panfry over medium-high heat until deep golden, about 15 min on each side.
Clarified unsalted butter	15 g	15%	⑤ Cool.
Potato juice, decanted from starch residue	300 g (from 700 g of potatoes)	300%	⑥ Vacuum seal with cooked potato skins and slices. ⑦ Cook sous vide in 80 °C / 176 °F bath for 1½ h.
Water	300 g	300%	⑧ Strain.
Salt	to taste		⑨ Season, and cool. ⑩ Vacuum seal, and refrigerate until needed.

(2009)

As it does for vegetable stocks, putting a broth in an ultrasonic bath for 30 minutes improves flavor extraction. This should be done after the sous vide cooking step.

PARAMETRIC RECIPE

FLAVOR-INFUSED LIQUIDS

Making an infusion is as elementary as making a cup of tea. Modern menus may refer to them as tisanes, tinctures, concoctions, or tonics, but they are all simply the steeping of an ingredient in a liquid to extract the flavor. Most infusions are made with water, but broths, juices, milks, and creams work well.

Add infused liquids to any dish to transform it. You can take inspiration from chef Michel Bras, whose dishes would seem somehow unfinished without the infused flavors of wild herbs and blossoms from his beloved Aubrac plateau. Chef Andoni Luis Aduriz incorporates the earthy perfume of wild herbs into the dishes he serves at Mugaritz in San Sebastián, Spain.

Rather than just pouring hot water over components or boiling them, we most often combine them cold, then warm them sous vide to infuse the flavors at a lower temperature that doesn't risk overextraction and bitterness. Keep your infusions sealed until use to prevent evaporation and oxidation from spoiling them.

INFUSING FLAVOR INTO A LIQUID

1 **Combine ingredient with cold liquid.** Quantities in the table Best Bets for Infused Liquids below are proportional to the weight of the liquid. For example, to infuse rice vinegar with lemongrass, add 10 g of crushed lemongrass for every 100 g of vinegar.

2 **Vacuum seal (optional), and cook.** Recommended cooking methods, temperatures, and times are given in the table. Sieve.

Best Bets for Infused Liquids

			Infusion				
Ingredient	(scaling)*	Method	(°C)	(°F)	(h)	Example use	See page
cured bacon, thinly sliced	30%	cook sous vide	85	185	2	bacon water	
black pepper, crushed	0.50%	infuse sous vide	3	37	12		
chili, dried	2%	infuse sous vide	3	37	12	Chinese broth	
cinnamon, finely crushed	3%	infuse sous vide	3	37	12	cinnamon dashi	4·118
coffee, ground	7%	infuse sous vide	3	37	12	beef jus	
ginger, thinly sliced	120%	blend, infuse	3	37	12	Chinese broth	
juniper, crushed	7%	cook sous vide	70	148	15 min	game broth	
lemon zest, grated	10%	infuse sous vide	3	37	12	broth for pasta	
lemongrass, thinly sliced	50%	cook sous vide	85	185	20 min	Thai or Vietnamese broth	
lemon verbena	30%	infuse sous vide	3	37	12	lemon verbena sponge	4·273
licorice root, grated	5%	infuse sous vide	3	37	12	broth for foie gras	
mushroom, dried	6%	cook sous vide	60	140	20 min	mushroom cappuccino	4·275
nutmeg, grated	0.2%	infuse sous vide	3	37	12		
Parmesan cheese, grated	80%	cook sous vide	85	185	12	Parmesan water	
prosciutto, thinly sliced	30%	cook sous vide	80	176	2	prosciutto water	
saffron threads	1.5%	infuse sous vide	3	37	24	tomato vinegar	5·65
star anise, crushed	3%	infuse sous vide	3	37	12		
tarragon	20%	infuse sous vide	3	37	12	beurre blanc, fish broth	
tea, black	3%	ultrasonic bath	85	185	5 min	bergamot sabayon	4·274
tea, green	2%	infuse sous vide	3	37	12		
tea, white	4%	cook sous vide	70	158	7 min		
paprika, finely ground	2%	infuse sous vide	3	37	3	goulash	
young pine buds	8%	boil and refrigerate	3	37	12	citrus seafood broth	
vanilla	1.5%	infuse sous vide	3	37	24	broth for foie gras	5·109

**(set weight of liquid to 100%)*

10

Seasoning with Salt and Other Flavor Enhancers

When cooks judge the flavor balance and seasoning of a dish, salt is typically checked first. Get the salt level wrong, and diners will quickly be distracted from their enjoyment of the food. Table salt enhances our perception of flavor, and so do nucleotides and monosodium glutamate (MSG), which are savory salts that trigger different taste receptors than salt does. You can enhance flavor in many ways besides sprinkling salt crystals over your food: anchovies, dried scallops, and shrimp paste all layer on tastes of the sea and the shore. Ingredients such as bacons, hams, and cheeses carry hints of the country, barnyard, and sometimes smoke. Soy sauce, fish sauce, miso, and natto are all fermented seasoning agents, and each has a certain tanginess and vegetal quality.

Salts	Taste	Aroma	(scaling)*	Note
salt	defines salty	none	0.5%–2.0%	most useful flavor enhancer in the kitchen; most people find 0.75–1% best for savory foods
monosodium glutamate	defines umami (also called savory)	none	0.1%–2.0%	found naturally in all high-protein foods; some people find >1% harsh and metallic-tasting
5′ ribonucleotides	savory	none	0.02%	found naturally in most foods; boosts existing savory flavors
Seasonings				
aged cheese	salty, sharp, acidic, strongly savory	varies greatly	3%–10%	hard cheeses like Parmesan contain both salt and glutamate
anchovy	salty and oily	fishy; roasted scent when cooked	0.2%–0.8%	used as a seasoning since the time of Imperial Rome
bacon	salty	smoky, fried, meaty	3%–15%	can quickly overwhelm a dish
capers (salt-packed)	salty, slightly bitter and astringent	mustard oil, hint of thyme	2%	add at the last moment; high heat degrades aromas
cured meats	salty, strongly savory, slightly sweet	varies greatly; often nutty, fruity, and floral	5%–15%	use with moderation; combination of salt, sugar, fat, and Maillard flavors with smoke aromas is powerful
dried scallops	slightly sweet	pungent, slightly fishy, cured	3%–5%	used primarily in Asian cooking
fish sauce	salty, strongly savory, slightly sweet	pungent, slightly fishy	2%–10%	adds depth and savory flavor; tastes better than it smells; a favorite in ancient Rome
garlic	pungent, slightly sweet, enhances savory	sulfurous	1%–7%	when garlic is crushed and raw or lightly cooked, its allicin compounds trigger pain and temperature receptors in the mouth, thereby enhancing flavors
Marmite or Vegemite	salty, strongly savory	yeasty, meaty, malted	0.3%–1.5%	adds meat-like flavors to vegetarian dishes
miso, red	slightly sweet, savory	strong, roasted, hint of cocoa	1%–8%	includes all three primary salts listed above; pungency varies with degree of fermentation
miso, white		mild, caramel, toasty	1%–8%	
natto	salty, savory	pungent, fermented, roasted, cheesy	1%	
shallots	pungent, slightly sweet, enhances savory	sulfurous	5%–30%	similar to garlic but does not cause onion breath because sulfurous compounds do not enter bloodstream
shrimp paste	salty, slightly sweet, savory	pungent, slightly fishy, cured	1%–3%	used primarily in Southeast Asian cooking
soy, dark	salty, slightly sweet, mildly astringent	strong, fermented, roasted, molasses	2%–5%	tastes and aromas vary greatly among styles and brands
soy, white		mellow, slightly sweet, floral	2%–5%	
tomato	sweet, acidic, savory	fruity, musky, sometimes floral	5%–9%	rich source of sugars, acids, and salts when ripe; enhances roasted aromas when browned with meats
Worcestershire sauce	salty, sweet, savory, acidic, slightly spicy	fermented, roasted, molasses, spicy, vinegary	2%–5%	has many applications; underused as a seasoning; a distant relative of Roman fish sauce (garum)

*(*set weight of food being seasoned to 100%*)

THE TECHNOLOGY OF

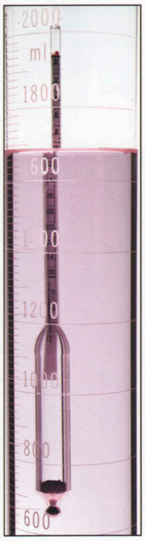
Measuring Salinity

Seasoning with salt "to taste" is an unavoidable directive, but one with some surprising pitfalls. Not only do individual tastes differ, but the same person can perceive saltiness differently in different situations, depending on factors as varied as the sugar content of the food or the taster's level of hydration.

Salinometers allow cooks to quantify the level of salt in that momentary taste and thus help to make recipes more consistent and reproducible. Salinometers are also convenient tools for gauging whether brines are reusable.

There are several kinds of salinometers. The most accurate is based on electrical conductance. Others use a weighted float to measure refraction or the density of the liquid, but these can confuse salt and sugar concentrations.

Even after quantifying the salinity of a dish with this tool, resist the urge to remove saltshakers from the table. Remember, the diner may not taste even consistent concentrations of salt in the same way the chef does.



EXAMPLE RECIPE

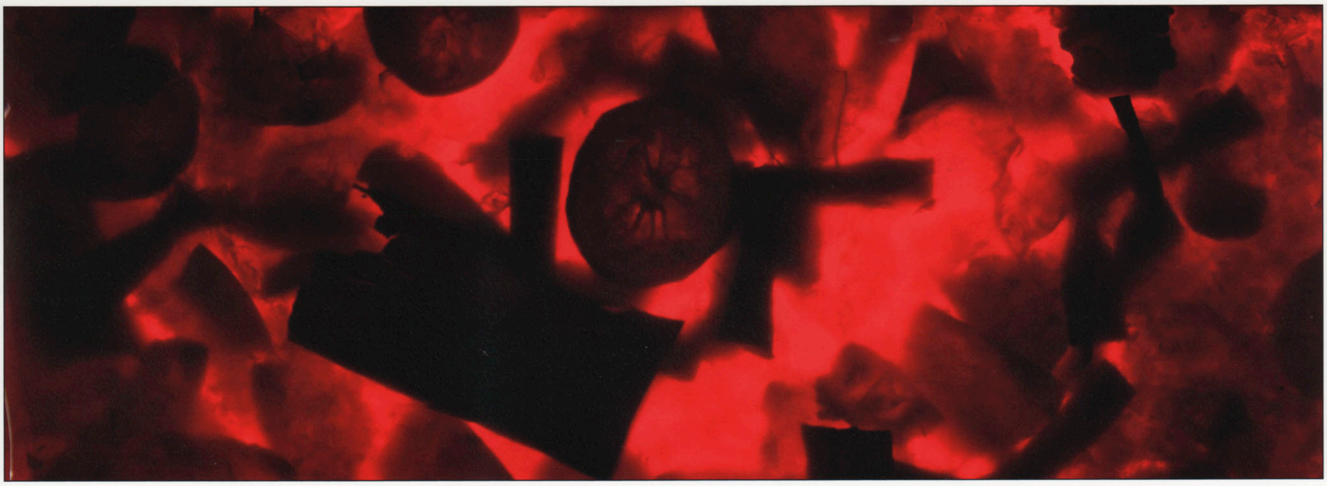
SOUS VIDE PONZU ADAPTED FROM KYLE CONNAUGHTON

Yields 1.95 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Yuzu	120 g (about four whole)	17%	① Grate zest, and juice flesh.
Sudachi (optional)	35 g	5%	
Mirin	700 g	100%	② Combine in pan, and simmer until reduced to about 80% of original volume.
Sake	65 g	9.5%	
Kombu (Rishiri if available)	15 g	2%	③ Toast over open flame on all sides.
Tamari soy sauce	550 g	79%	④ Combine with citrus zest and juice, kombu, and reduced mirin-sake mixture.
Red rice vinegar (yusen)	525 g	75%	⑤ Vacuum seal.
Shoyu soy sauce (usu-kuchi shoyu)	110 g	16%	⑥ Refrigerate for 3 wk.
Bonito flakes (katsuobushi)	10 g	1.4%	⑦ Strain.
			⑧ Use immediately, or vacuum seal and refrigerate until needed.

(original 2008)

Japanese flavor combinations often include multiple variations on the umami flavor theme. In this recipe, different soy sauces and kombu provide umami notes, which are balanced by the bright yuzu citrus flavors.



PARAMETRIC RECIPE

ACIDIFIERS

Sourness is one of the basic tastes and is as essential as saltiness for balancing the seasoning of a dish. But it is too often underused. Including an acidifier among your ingredients won't necessarily make the food sour—it can instead add brightness. An acid also can activate the salivary glands at the sides of the diner's mouth, helping to distribute flavors more throughout the palate. The end result is a dish with greater depth and intrigue.

The table Best Bets for Lowering pH below can help in choosing an acidifier that will complement the flavor and origins of the recipe. Fruits and fruit juices make excellent acidifiers but may add too distinctive a flavor in certain dishes. Vinegars are good for salads and for earthy, savory dishes. Try squeezing a lime into a spicy curry or adding balsamic vinegar to a rich meat sauce.

If your aim is to increase overall tartness but not to add a specific flavor, a pure edible acid may be a good option. For more control over the results, dilute the acid by adding 10 parts water for every one part acid. Citric acid adds the tang of lemon and lime without their distinctive flavors, whereas malic acid subtly introduces the fresh, fruity zip of green apples.

The table Typical Acid Concentrations on the next page offers starting points for determing the right amount of an acidifier to use for various applications. Some of the ranges are quite wide because foods vary greatly both in their natural pH and in their natural ability to resist a change in pH. This so-called buffering capacity explains why you can add one spoonful of vinegar after another to a soup and taste no noticeable change until some threshold amount, beyond which the soup suddenly tastes sour. A well calibrated pH meter will help ensure consistency.

Best Bets for Lowering pH

Ingredient	Typical pH	Flavor profile	Example uses
Vinegar (pH 2.4–3.4)			
cider vinegar	2.4	sharp, apple	salad dressing, marinade, coagulation
malt vinegar	2.4	bittersweet, hops, caramel	sauce, marinade
red wine vinegar	2.4	currant, tannic	dressing
rice vinegar	2.8	sweet, subtle, toasty	salad dressing, marinade, coagulation
sherry vinegar	3.4	sweet, oak, cherry, earthy	salad dressing, finishing meat sauce
white wine vinegar	2.8	clean, bright, green grape	salad dressing, fish broth, butter sauce
Citrus (pH 1.8–3.9)			
grapefruit juice	3.7	floral, light citrus, coffee	finishing sauces, seasoning seafood dishes
lemon juice	2.3	bright, perfumed	dressing, sauce, balancing oil
lime juice	1.8-2	sharp, coconut, pine	sour broth, finishing fruit and vegetable water
orange juice	3.9	sweet, neroli	mellows other acids
Pure acids (diluted 1:10 with water; pH 2.4–2.9)			
acetic acid (vinegar)	2.9	pungent	wine sauce, dressing
ascorbic acid (vitamin C)	2.9	crisp	color preservative
citric acid (citrus)	2.4	sharp, citrus	fruity sauce for fish
lactic acid (dairy)	2.6	buttermilk, sour cream	dairy applications, enhancing fermented flavors for quick kimchi and sauerkraut
malic acid (apple, cherry)	2.4	tangy with light fruit notes	finishing glaze, sauce, raw fruit sauce, and water
tartaric acid (grape)	2.4	heavy acidity, light flavor	reduction, wine sauce, fruit sauce
Tart fruit (pH 2.5–4.2)			
red currant	3.1	tannic, bitter, berry	glaze or sauce for red meat, game
rhubarb juice	3.4	astringent, herbal, mellows when cooked	sauce or broth for fish, foie gras
tamarind paste	3.7	sour, caramel, pungent	sauce, sweets, dressing, broth
tomato juice	4.2	earthy, complex, vegetable	vegetable broth, dressing
verjus	2.7	tannic, grape must	finishing sauce (best used raw)
gooseberry juice	2.6	bitter, sour, floral	dressing for shellfish and oysters

Typical Acid Concentrations

Acid type	For seasoning (pH 5.5–6.5)	For souring (pH 4.0–4.5)	For vinaigrettes (pH 3.0–3.8)	For pickles (pH 2.3–3.0)
kitchen acids	0.2%–0.5%	1%–3%	3%–6%	5%–10%
citrus juice	1%–3%	5%–15%	10%–100%	65%–100%
astringent fruit	3%–10%	10%–50%	10%–60%	65%–100%
vinegar	1%–5%	25%–75%	30%–100%	50%–100%

Kitchen acids include ascorbic, acetic, citric, lactic, malic, and tartaric acids. Note that the wide ranges in this table are due to variations in the initial pH and in the buffering capacity of the food.

EXAMPLE RECIPE

SEAWEED VINEGAR

Yields 250 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Cider vinegar	200 g	100%	① Combine.
Muscovado sugar	26 g	13%	② Bring to a simmer.
Palm sugar	16 g	8%	③ Stir mixture until sugar is dissolved, and reserve warm.
Coriander seeds, toasted and crushed	2 g	1%	
Kombu, shredded, soaked for 45 min in warm water, and drained	30 g	15%	④ Combine, and add to vinegar mixture. ⑤ Vacuum seal and steep at room temperature for 12 h.
Ginger, grated	3 g	1.5%	⑥ Strain.
Whiskey	10 g	5%	⑦ Whisk into strained vinegar.
Salt	to taste		⑧ Season.

(2010)

EXAMPLE RECIPE

ELDER FLOWER VINEGAR

Yields 700 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
White wine vinegar	500 g	100%	① Whisk together.
Elder blossoms, thoroughly washed	170 g	34%	② Vacuum seal. ③ Infuse refrigerated for at least 1 week.
Malt vinegar	100 g	20%	④ Strain.
Rice vinegar	100 g	20%	⑤ Use to dress salads or as a condiment for raw shellfish.
Sugar	65 g	13%	
Malic acid	2 g	0.4%	

(2010)

Flavored vinegars, like those on this page, or various commercial varieties, are one way to combine acidity with complementary flavors.

Many foods have compounds in them that will react with any acid you add, which tends to neutralize the acid. Chemists call this property buffering. A food with a high buffering capacity requires more acid to be added to reach a given level of final acidity than one with a low buffering capacity. Because this capacity varies from food to food, it is hard to give precise numbers on how much acid to add. A pH meter is the best way to achieve consistency.

THE TECHNOLOGY OF

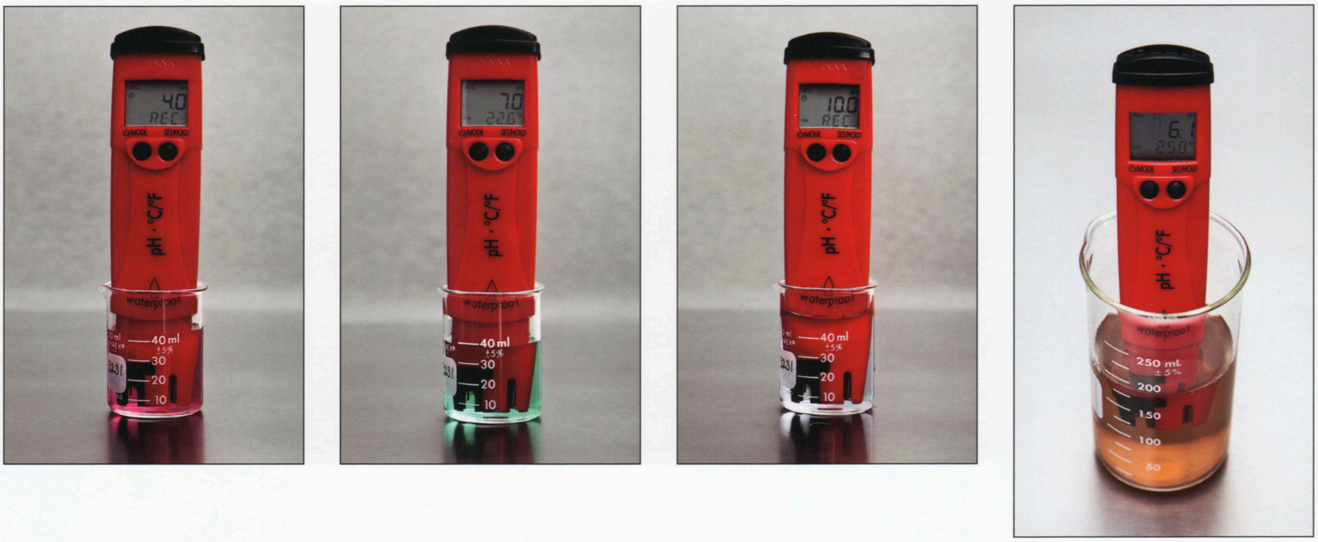
Measuring pH

Consistency is often a virtue in the kitchen, particularly with basic building blocks like stocks and sauces. A pH meter that inexpensively and quickly measures the acid content of liquids is a convenient way to ensure that acidity is consistent from one batch to the next.

Instructions vary from model to model, but the basics involve dipping the probe in the liquid you want to measure and waiting for the reading to stabilize, which can take up to a minute. The meters must be recalibrated regularly (ideally daily in a busy kitchen) by using solutions available from the manufacturer. To avoid cross-contamination, clean the probe as recommended after every use.

You can buy solutions formulated to pH values of exactly four, seven, and 10 to use in calibrating your pH meter. Refer to the manufacturer's instructions to calibrate your meter. Most devices have a special calibration mode. To use it, you typically dip the probe into one of the calibration solutions, wait for the reading to stabilize (indicated by a beep or flash), then rinse the meter quickly in tap water. Repeat with the other preformulated solutions, then reset the meter to measuring mode for use.

You can buy solutions formulated to exactly to pH values of exactly four, seven, and 10 (above and below) to use in calibrating you pH meter. Refer to the manufacturer's instructions to calibrate your meter, but most devices have a special calibration mode.



The color of red cabbage juice (below) varies with pH.

SEASONING WITH WINE, BEER, AND SPIRITS

To cooks, wine and other beverages containing alcohol can be a type of seasoning. They use them to awaken the palate or to help liberate aromatic compounds. The addition of just a tiny shot can add depth and character to dishes. Because of the tremendous variety of bitter, sour, and sweet profiles available in wines, beers, and liquors, they serve an important role as multidimensional flavoring agents.

How to choose the perfect alcoholic beverage to match a particular food is a subject complex enough to fill its own book. Go with your own personal preferences, or follow the lead of geography or history as well as flavor. The right Scotch whiskey adds mossy flavors of the field to wild game stock, for example. Dry sherry complements garlicky tapas and braised Spanish octopus. A splash of Shaoxing enlivens even simple stir-fries. And sake is a must in Japanese stews and hot pots.

Pay attention to the proof of any spirit you add, and remember the high volatility of ethanol. Will the peppery, raw zip of a strong liquor enhance the flavors and aromas of your dish at presentation? Then add it shortly before service. Would your dish be better served with the acidity, sweetness, fruitiness, or herbal or woody undertones of a reduced elixir? Then let the liquor merge with the other ingredients as it cooks. Remember that alcohol cannot escape from a sealed sous vide bag.

Chefs flame the contents of their sauté pans to burn off raw alcohol and adjust the flavor. We rather like that raw taste and do not take that step. Choose the approach that suits you.

Best Bets for Adding Flavor with Alcohol

Ingredient	Broth (scaling)*	Sauce (scaling)*	Characteristic aromas	Alcohol content	Example uses	See page
aquavit	2%–7%	10%–30%	caraway, fennel	high	finishing raw, cold items	
Armagnac	1%–5%	10%–30%	smoke, oak	high	glaze, sauce, adding body and subtle flavors	5·17
beer or ale	10%–20%	15%–40%	malt, barley, bitter	low	meat sauce, glaze, adding grain flavors and bitterness	374
Cognac	2%–6%	10%–30%	smoke, oak, tobacco	high	glaze, sauce, adding body and subtle flavors	5·128
gin	1%–5%	10%–30%	juniper, pine, cassia	high	marinade and game sauce, adding spice	5·35
Madeira	5%–10%	20%	pepper, plum	low to moderate	sauce with dairy or mushrooms, adding sweetness and fruit flavors	
pastis	1%–5%	1%–5%	anise, licorice, sugar	moderate	seafood broth, soup	
port, red	10%–20%	15%–40%	cherry, berry, oak	low to moderate	broth and sauce	4·53
port, white	15%–40%	15%–100%	pear, sour grape	low to moderate	broth, sauce, adding sweetness	5·110
sake	5%–16%	25%–75%	light pepper, honeydew	low	fish broth, adding sweetness and a little spice	5·197
Shaoxing	3%–15%	10%–30%	sweet rice, floral	low to moderate	pork, fish sauce, adding acidity and sweetness	5·167
sherry, dry	3%–8%	15%–40%	almond, hazelnut	low to moderate	shellfish broth, adding body and tannins	5·31
sherry, sweet	5%–10%	5%–20%	cherry, currant	moderate	glaze broth, adding sweetness and complexity	
vermouth	5%–20%	15%–40%	chamomile, cardamom	moderate to high	fish broth, sauce, enhancing flavors	5·233
vin jaune	2%–20%	25%–74%	walnut, almond, melon	low to moderate	broth, sauce, adding acidity and body	5·113
whiskey	7%–10%	20%–60%	smoke, leather, vanilla, char, peat	high	glaze, adding sweet and smoky flavors	5·66
wine, red	7%–15%	25%–100%	tannin, berry, oak	low to moderate	glaze, meat sauce, adding complexity and fruit flavors	344
wine, white	7%–15%	25%–100%	apple, pear, floral	low to moderate	broth and sauce, adding acidity and complexity	5·170

*(*set weight of broth or sauce to 100%*)

INFUSING ESSENCES

When you catch a whiff of ginger root or orange peel, almonds or cinnamon bark, your nose is sensing numerous volatile chemicals and integrating those myriad sensations into a perceived scent. Sometimes, a few of the fragrant components are so dominant that you can identify the source from those odors alone. Distill, extract, or press out these telltale aromatic chemicals, and you get the plant's essence.

Vendors sell essential oils and related extracts for use in making perfume, scented candles, soap, cosmetics, household cleansers, incense, and aromatherapy products. Indeed, the fragrances added to such items are often the most distinguishing feature of a brand.

These concentrated olfactory essences can be especially useful in the kitchen because it is the aroma that gives a food most of its characteristic sensory signature; any response our tongues have to the sweet, salty, savory, or bitter taste of the food only contributes to the overall flavor. What we smell in our nose is as important or more so than what the mouth tastes to the flavor of food. Aromatic essences offer limitless ways to enhance the overall flavor. Add a few drops of the essential oil of coriander to the vinaigrette in a crabmeat salad, or dribble a bit of spearmint oil into a mojito, and you can inject surprise and intrigue into the resulting gustatory experience. The aromas of ylang ylang or orris root can imbue a dish with an exotic flavor that is haunting.

To fully embrace the aromatic possibilities of essences and to leverage their potential to sculpt flavor, the Modernist cook needs to think the way perfume designers do. Like an exquisite perfume, many deeply satisfying flavors are layered constructions. A food's aroma comprises a hierarchy of fragrances that includes long-lasting, foundational olfactory notes (known as base notes); less enduring middle notes that add structure and complexity; and top notes, which are the most fleeting components of a food's smell but are often the elements that provide the key olfactory cues that differentiate one dish from all others.

Getting at the Essence

You can buy commercially processed essences of many kinds, but you may want to make them yourself. Over the centuries, cooks have developed numerous ways to extract the aromatic essences of a plant, including pressing the oil out, dissolving it in fat, and distilling it.

Citrus peels and other plant tissues that are rich in volatile oils will give them up when pressed while cold. Steam distillation is more common for spices and works with a wider range of fragrance materials to yield **essential oils** from botanical sources. The distilling apparatus sends a flow of steam through a tube and into a vessel containing the target plant tissue, which may include roots, stems, leaves, seeds, petals, or other components. The steam vaporizes any volatile chemicals that boil at a temperature lower than that of the steam. The hot water vapor then carries the liberated volatiles into a water-chilled coil, where they condense from vapor back to liquid form. Finally, the liquid condensate drips into a collection container.

This condensate is a mixture of two parts, which gradually separate from one another. An aromatic hydrosol contains some of the more

Essential oils, extracts, resins, concretes, and absolutes are the domain of perfumers and flavorists, but they offer limitless possibilities for creativity in the kitchen. Each kind of essence conveys a different aspect of a botanical's fragrance.

10

For more on how a rotary evaporator (or rotavap) and a Genevac Rocket Evaporator work, see page 384.

In a polar molecule like water, the electric charge is distributed less uniformly than it is in a nonpolar molecule like hexane, which contains electrons shared equally among two atoms. For more on polarity and solubility, see chapter 6 on The Physics of Food and Water, page 1·294.

Supercritical carbon dioxide is used industrially for many purposes, including extracting caffeine to make decaffeinated coffee. For more on the supercritical state of matter, see page 1·326.

water-soluble volatiles and settles to the bottom. Rose water is an example of this part. At the same time, the second part, consisting of the actual essential oil that is much richer in those aromatic compounds that don't dissolve in water, rises to the top. You can use a pipette, dropper, siphon, or laboratory separatory funnel to isolate these two fluids from the mixture. Industrial-scale steam-distillation systems often have valves at the top and bottom of the collection vessel to allow for easier separation.

Steam distillation works well in many circumstances, but it does have a drawback: the high heat involved can alter or even destroy some of the more fragile aroma molecules. Technological solutions to this problem, such as a rotary evaporator or a vacuum condenser, are now available, albeit expensive.

Solvent extraction offers a way to extract a botanical essence without heat. This method uses solvents, such as ether or hexane, that are nonpolar and usually hydrophobic ("water-hating") and thus reject contact with water. Most of the organic volatile compounds in plant oils also are relatively nonpolar, and they typically dissolve readily in a nonpolar solvent.

When you mix a nonpolar solvent with a food, a semisolid or pastelike substance forms. Called **concretes** or **oleoresins**, these substances contain some of the waxes and resins that were in the food as well as extracted aromatic oils. Once extraction is complete, the nonpolar solvent must be removed, usually through distillation or evaporation. To use the concretes or oleoresins, you usually make what specialists call an **absolute** by washing the material with alcohol and then filtering. The result is a solution of flavor in alcohol, which is known as a **tincture**.

Other nonpolar solvents include fats that are themselves hydrophobic can be used to extract flavors—a property that perfumers have exploited for centuries in a classic fragrance-harvesting procedure called **enfleurage** (see page 323).

Ethanol (pure grain alcohol) can also make a useful solvent—many cooks have ethanol solutions sitting in their pantries in the form of vanilla extract. Because ethanol lies somewhere between water and ether on the polarity scale, it may not extract as many of the organic compounds as hexane does, but it has the benefit of extracting some of the water-soluble **tastants** that nonpolar solvents don't capture. This extract is another example of a tincture. In the context of mixed drinks, such tinctures are often called **bitters**.

Going Supercritical

A still more challenging approach to extraction avoids both heat and the need to use (and later remove) a petroleum-derived solvent such as hexane, which is mildly toxic. The method is called **supercritical fluid** extraction—"supercritical" referring to the special state of matter in which a substance behaves like both a gas and a liquid at the same time.

When carbon dioxide is pushed into a supercritical state by the right combination of temperature and pressure, it infiltrates food deeply. Once inside, the carbon dioxide functions like a liquid solvent and extracts organic flavor compounds as concretes. The supercritical solvent can then easily exit the food, gas-like, carrying the extracted aromatic compounds with it.

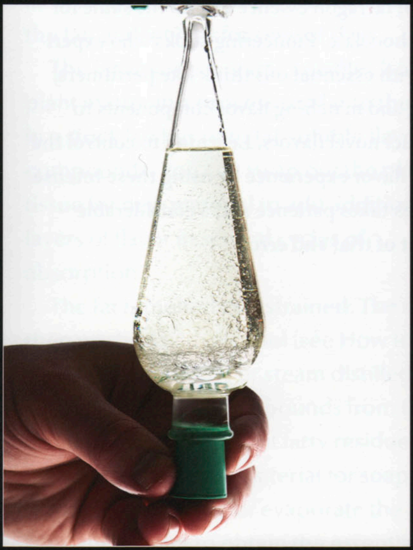
Then just by dropping the pressure, you can harvest an absolute from the mixture, while simultaneously separating it from the waxes and resins. The carbon dioxide flashes away instantly as a gas. This process yields an extract from, say, rose petals, that has a different (but not necessarily better) character than that obtained via steam distillation. Each method delivers a distinct set of aromas for the enthusiast to investigate.

Because so many desirable aromatic volatiles in foods dissolve in fats and oils, many cooks often inadvertently remove these substances when they skim fat off stocks. Fat washing can work well in these circumstances.

The general idea of fat washing is to mix the flavor-rich oil with alcohol and then shake the mixture to emulsify the two temporarily (see How to Wash Citrus Oil, next page). While the alcohol and oil are in intimate contact, some of the flavor compounds migrate from the oil into the alcohol. After a resting period of several hours or longer, the two phases naturally separate again, just as oil and vinegar do, but now many of the flavor compounds have been dissolved in the ethanol. You can add the flavored alcohol to your dish and just apply a little heat to drive off enough of the ethanol to ensure that the result doesn't taste of booze.

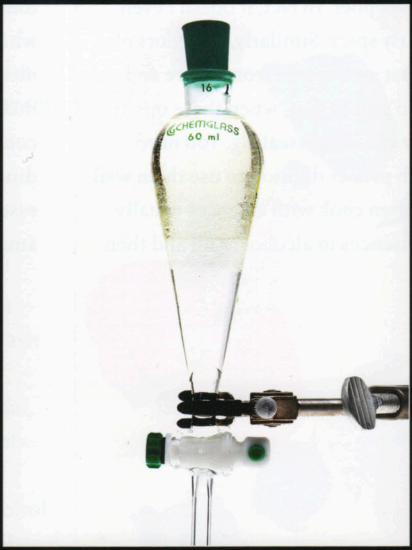
HOW TO Wash Citrus Oil

Citrus oils are fresh and aromatic—wonderful in flavored drinks. Add them to water, however, and the mixture will turn cloudy or the droplets will rise to the surface to form spots of oily sheen. To fully enjoy citrus oils in a clear liquid, such as a citrus soda, you need to capture the aroma and flavors in a water-soluble form by "washing" the oil. The process is as simple as shaking the oil with water and alcohol, then setting it aside to separate and clarify. If you do this in a laboratory separatory funnel, it is then easy to drain off the flavored water. This technique works for virtually any essential oil, but some varieties are harder to cleanly separate than others. If the essence will not clear, add five parts sugar syrup or glycerin for every one part of water to aid separation. When making citrus sodas, use one to five parts of finished essence for every 1,000 parts water. Keep flavored waters sealed to preserve their flavor and aroma.

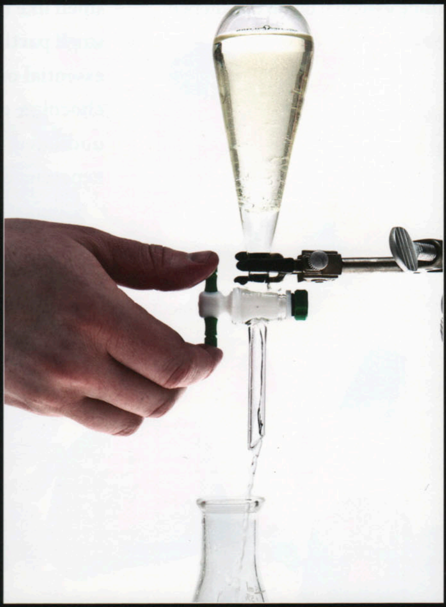


1 Combine the ingredients in a separatory funnel with the stopcock closed (not shown). Use 10 parts essential oil, 40 parts distilled water, and 50 parts pure alcohol (either ethanol or Everclear), or use a high-proof vodka that has been run through a water filter a few times in place of both the water and the ethanol.

2 Stopper the funnel and shake until the mixture becomes cloudy.



3 Let stand undisturbed until the mixture separates. The oil rises to the top. When the liquid is clear—after a day or even a week of resting—the essence is ready. Longer time will yield a more intense extraction.



4 Remove the stopper, open the stopcock, and drain the flavored water through a coffee filter. The filter will remove any waxes and impurities. Close the stopcock just before the oil starts to emerge.

EXAMPLE RECIPE

HAZELNUT OIL EXTRACT

Yields 300 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Roasted hazelnut oil see page 367 (or store-bought)	300 g	100%	① Combine in separatory funnel. ② Shake vigorously for 2 min.
Vodka	300 g	100%	③ Allow oil and alcohol to separate overnight. ④ Decant alcohol from bottom of funnel. ⑤ Use hazelnut oil–infused alcohol to season broths or sauces without adding fat.

(2010)

Working with Essences

Chef Daniel Patterson has written an entire cookbook called *Aroma: The Magic of Essential Oils in Foods and Fragrance*. It has many ideas for using essential oils in the kitchen.

Essences are to flavor what Klaxon sirens are to sound. Skilled flavorists know that essences can be powerful tools for intensifying flavor, but they must be wielded with finesse. Essences can be deceptive because in such a concentrated form, many substances smell nothing like they do when they are highly diluted in food or drink. The essential oil of black pepper, for example, does not smell like black pepper. In fact, it doesn't even smell particularly spicy. Similarly, the odors of essential oils that are derived from coffee and chocolate are so potent that, when these oils are undiluted, they can be nauseating. You need experience with proper dilution to use them well.

Chefs who often cook with essences usually predilute the essences in alcohol or oil and then Sometimes they may ask servers to add such oils in sparing quantities to dishes right at the table.

One common use for essential oils it to replenish flavors lost to heat during reduction. The more ambitious cooks use them to propel dishes into culinary terra incognita. Adding a single drop of the essential oil of ginger to a chilled carrot soup can give the dish flavor dimensions entirely different than freshly grated ginger alone could. A touch of tarragon essence can do the same for white chocolate. Pioneering cooks who experiment with essential oils think like perfumers, mixing and matching flavor components to construct novel flavors. Learning to control the diner's flavor experience by using these intense essences takes patience and a considerable amount of trial and error.

These vials show an essential oil diluted at various ratios. Serial dilutions make it easier to measure out the small quantities needed.

THE TECHNIQUE OF

Enfleurage

One of the oldest (and most laborious) techniques for extracting fragrances from botanical tissues is enfleurage. Smear a framed glass plate with a thin layer of a few millimeters of solid fat such coconut fat or lard, then press the botanical material into the fat, and let it sit for several days.

The fat absorbs organic volatiles from the plant matter in a process similar to the way oil in a stock latches onto fat-soluble flavor compounds. You can swap out the plant tissue for new material to add additional layers of flavor in several cycles of absorption.

The fat is melted and strained. The oil is then washed with alcohol (see How to Wash Citrus Oil, page 321) or steam distilled to retrieve the aroma compounds from the fat, leaving behind a fragrant fatty residue that makes a fine starting material for soap. Collect the distillate or evaporate the alcohol from the extract to obtain the essential oil.

A culinary variation on this basic technique infuses oil rather than solid fat. You place macerated botanical material directly into hot oil (for example, in a sous vide bag). You can use a strainer to swap in fresh plant material, followed by a final fat wash with ethanol and a reduction to retrieve the essence and make it water-soluble.

THE SAFE HANDLING OF
Natural Essences

Essential oils are chemical concoctions that have been concentrated to degrees not normally found in nature. Although they open up fantastic flavoring opportunities, these essences require careful handling to be used safely. Many are extremely volatile, even flammable. Essences should always be stored according to the guidance given in the materials safety data sheet that a reputable seller will provide. Typically, a dedicated refrigerator should be used to store the sealed vials to reduce the chance of an accident. Keeping essences refrigerated in sealed containers is good practice anyway; it helps to preserve them at peak quality.

Many essences are made to be used in perfume. If you are using them in food, make sure they are safe to eat. One smart strategy is to think of essences as medicines. Indeed, some have long been used for medicinal purposes. A warning notice that states "keep away from children" is fully warranted. Pregnant women should also be cautious; essential oils are chock-full of botanical compounds that have a wide range of biological effects.

Without dilution, some essential oils can irritate the skin, increase its vulnerability to sunlight, or spark allergic reactions. Wear rubber gloves when handling them.

Pay attention, too, to the provenance of the oils you use. Even though the essential oils that are used by perfumists are formulated from chemicals that are generally regarded as safe (see page 1·254), essential oils that are intended strictly for making fragrances are not always food-grade. Never cook with any ingredient that is not specifically intended for human consumption. The USDA maintains an extensive list of essences that are approved for use in food, and specialist essence resellers should be able to provide you with details on the food-grade status of any essence they will supply and what the maximum permissible concentrations in food are. When in doubt, don't use it.

For the same reason, never extract or distill essential oils from nonfood items such as tobacco, leather, or soil. These unusual sources might be a way to create entirely new flavors, but the results for the diners could be dire—even lethal.

Essential oils are powerful sources of flavor but must be used with care because they are highly concentrated. In addition, the solvents they contain can be flammable.

Best Bets for Using Essences and Extracts in Cooking

The variety of essences that are commercially available is huge, but not all of them can be eaten. Those below include the most popular essences, as well as a few unusual ones, that are used as food flavorings and that are generally recognized as safe.

Perfuming food is an art; there are no consistent rules governing how much of any particular essence to use in a given dish. A single drop of rose oil might be ideal in one kind of dish, whereas another might require ten drops to produce the desired effect.

In general, you should dilute most essences with neutral oil or ethanol first; use 100 g of oil or alcohol for every 1 g of essence. Alternatively, "wash" the essences in a mixture of alcohol and water to prepare a tincture that you can then use directly, see page 321.

The quantities given below are good starting points for most foods; increase the quantity by 10%–25% for fatty foods. Further refinement may be needed to suit a particular recipe. Amounts are given as a proportion of the weight of the food; to season a sauce with black-pepper extract, for example, use 0.5 g of prediluted extract for every 100 g of sauce.

Essence	(scaling)*
allspice	0.2%
almond oil (bitter)	0.1%
angelica root	0.07%
Angostura bark	0.07%
anise, green	0.2%
asafetida	0.1%
basil	0.5%
bergamot	0.3%
black pepper	0.5%
buchu leaf oil	0.07%
camphor	0.1%
caraway	0.2%
cardamom	0.2%
carrot seed oil	0.2%
cassia	0.2%
cassis bud	0.2%
cedarwood	0.2%
celery seed	0.2%
chamomile (German)	0.2%
chamomile (Roman)	0.2%
cinnamon	0.2%
citronella	0.2%
clove	0.2%
coriander leaf	0.2%
coriander seed	0.2%
cumin	0.2%
dill	0.2%
elder flower	1%
eucalyptus	0.1%
fennel	0.1%
fir (pine needle)	0.1%
galangal root	0.07%
galbanum	0.07%
garlic	0.07%
geranium	0.1%
ginger	0.5%
grapefruit	0.3%
hops	0.2%
hyssop	0.07%
jasmine	0.07%
juniper	0.1%
labdanum ciste	0.07%
lavender	0.07%
lemon	0.3%
lemon verbena	0.3%
lemongrass	0.2%
licorice root	0.5%
lime	0.3%
mace	0.07%
mandarin	0.2%
mustard	0.07%
myrrh	0.2%
neroli (orange flower oil)	0.07%
nutmeg	0.1%
oak moss	0.1%
olibanum (frankincense)	0.07%
onion	0.2%
orange	0.3%
orris	0.07%
patchouli	0.07%
peppermint	0.2%
petitgrain (citrus leaf)	0.1%
rose (attar of roses)	0.07%
rosemary	0.2%
rosewood	0.1%
sage	0.1%
sassafras	0.1%
spearmint	0.2%
star anise (badiane)	1%
thyme	0.1%
tuberose	0.2%
turmeric	0.8%
valerian	0.1%
vanilla	1%
violet blossom	0.3%
violet leaf	0.3%
wintergreen	0.1%
wormwood	0.07%
ylang-ylang	0.1%

**(set weight of food to 100%; predilute essences with 100 g of oil or alcohol for every 1 g of essence)*

PARAMETRIC RECIPE

EXTRACTING FLAVOR WITH ALCOHOL

Many flavor components dissolve in alcohol but not in water. In the flavoring industry, alcohol infusions are called tinctures. Such extracts have many culinary uses, such as adding aroma to a sauce or broth. A tincture made from browned butter can supply a nutty, buttery intensity without adding any fat.

A few tinctures, such as vanilla or almond extracts, are readily available. But in most cases you need to make your own tincture by vacuum sealing aromatic ingredients with alcohol in a sous vide bag. If available, use pure ethanol (such as Everclear); otherwise use a good-quality, neutral spirit such as vodka. Taste the infusion from time to time to judge the development of the flavor. When the flavor is intense enough, strain out the solids, and store the tincture sealed and refrigerated.

The table below suggests typical concentration ranges to use for preparing and working with tinctures. Add the extract just before serving for the maximum flavor impact.

EXTRACTING FLAVOR WITH ALCOHOL

1 **Select and prepare ingredient.** The table Best Bets for Extracts below suggests a number of good options.

2 **Vacuum seal ingredient with neutral vodka.** Quantities indicated in the table are proportional to the weight of the vodka. For example, use 25 g of chili for every 100 g of alcohol.

3 **Infuse.** Recommended infusing temperatures and times are listed in the table. Some preparations benefit from cooking; for others, infusion at refrigerator temperatures does a better job of capturing their delicate flavors.

4 **Sieve.** Reseal, and refrigerate until needed.

5 **Add recommended concentration of alcohol extract to broth or sauce.** For example add 4 g of brown butter extract for every 100 g of broth or sauce. Adding more than 5% will make the alcohol flavor perceptible.

Best Bets for Extracts

		Infuse					
Ingredient	(scaling)*	(°C)	(°F)	(h)	Example concentration**	Example use	See page
bay leaf, fresh	1%	60	140	4	5%	fish sauce, broth	376
brown butter, melted	100%	65	149	5	4%	vegetable broth	374, 5·158
butter, melted	100%	65	149	3	4%	popcorn broth	
chili (dry), crushed	25%	refrigerate		24	2%	Sichuan-style broth	
cinnamon stick, crushed	5%	60	140	4	3–4%	meat sauce	304
citrus zest, finely grated	27%	50	122	3	3%	fish sauce, broth	
coffee bean, ground	20%	refrigerate		12	3%	meat sauce, redeye gravy	5·101
coriander seed, crushed	20%	60	140	3	5%	seafood sauce	
fennel seed	5%	3	37	24	3–4%	pork broth, Parmesan jus	
ginger, thinly sliced	25%	60	140	4	3%	Chinese broth	
roasted hazelnut oil	100%	65	149	3	8%	root vegetable broth	
nutmeg, grated	7%	refrigerate		24	2–3%	guinea fowl consommé	
rosemary	10%	refrigerate		24	1.5–2.5%	lamb broth, lamb jus	
saffron threads	1%	refrigerate		24	0.6%	cream sauce	
star anise, crushed	5%	60	140	4	4%	oxtail consommé	376
thyme leaf	10%	60	140	4	3–4%	beurre blanc	
vanilla bean, split	5%	refrigerate		24	3%	sauce or broth of foie gras or lean fish	

*(*set weight of vodka to 100%*) **(*set weight of broth or sauce to 100%*)

EXAMPLE RECIPE

HOUSE BITTERS

Yields 500 g

INGREDIENT	QUANTITY	SCALING
Vodka	500 g	100%
Kumquat, thinly sliced	40 g	8%
Burdock root	12 g	2.4%
Vanilla beans, halved	12 g	2.4%
Orange zest	10 g	2%
Gentian flowers	6 g	1.2%
Cinnamon	5 g	1%
Cloves	3 g	0.6%
Heather tips	2 g	0.4%
Anise seeds	1.5 g	0.3%

PROCEDURE

① Combine.
② Seal in glass bottle with airtight lid.
③ Shake bottle twice a week for 4 wk.
④ Pour mixture through fine sieve into sterilized bottle.

(2010)

EXAMPLE RECIPE

FINES HERBS EXTRACT

Yields 100 g

INGREDIENT	QUANTITY	SCALING
Vodka	100 g	100%
Chervil, thinly sliced	33 g	33%
Chives	33 g	33%
Parsley leaves, whole	33 g	33%
Tarragon, crushed	15 g	15%

PROCEDURE

① Combine and vacuum seal.
② Refrigerate for 24 h to steep.
③ Strain through fine filter.
④ Add 2%–5% of extract to season broth or sauce, or reseal and refrigerate until use.

(2010)

PARAMETRIC RECIPE

FLAVOR INFUSION INTO FATS

In Chinese cooking, one of the hallmarks of a skilled cook is his ability to flavor the cooking oil in a hot wok with aromatics so each taste of the finished dish carries their perfume. Oils are so mobile that they offer an effective way to disperse the aromas evenly. An infused fat allows you to add the essence without adding the ingredient, which simplifies the preparation of a dish.

Use neutral fats for clean-flavored infusions; use more flavorful fats, such as olive oil or butter, to complement the flavors of the aromatic. Some pairings—butter with molasses, for example—are even more multilayered and complex when married in an infusion.

We recommend cooking fat infusions sous vide because the sealed packaging prevents oxidation and evaporation. In general, sieve the oil after infusing, then repackage and chill the oil. Keep it refrigerated until use.

There has been public concern about the anaerobic environment of sealed, flavored oils as a risk for botulism. If the food in the packaging is moist enough, then this can be a problem. The best practice is to keep the infusion refrigerated. Sous vide times and temperatures have been gauged to pasteurize, not to fully sterilize, the infusion so it can be stored without refrigeration, which requires canning times and temperatures. Ensure that herbs are washed and dried thoroughly for safe sous vide infusion.

INFUSING FLAVOR INTO A FAT

1. **Wash and dry all produce thoroughly to prevent contamination of the fat.**

2. **Vacuum seal ingredient with fat.** The table Best Bets for Infused Fats, on the next page, lists many good combinations. Quantities are proportional to the weight of the fat. When making coffee butter, for example, add 55 g of coffee beans for every 100 g of butter.

3. **Cook sous vide to infuse the fat.** Recommended temperatures and times are given in the table.

4. **Place food in bag into an ultrasonic bath for 15 min to 1 h (optional).** Ultrasonic treatment enhances extraction and should be done while the food is still hot. Use the same bath temperature used for infusion or the highest setting possible. Or use a sous vide bath that has ultrasonic capability to do the infusion.

5. **Sieve, then refrigerate.** Do not sieve truffle or other infusions in which the flavorful flecks are desirable.

Best Bets for Infused Fats

Ingredient	(scaling)*	Fat	Cook sous vide, or infuse cold			Example use	See page
			(°C)	(°F)	(h)		
cured ham, thinly sliced	40%	peanut oil	70	158	8	add to XO sauce, season fresh melon	
dried chili, crushed	3%	sunflower oil	70	158	24	poach fish, season sauteed broccoli	next page
cocoa nib, crushed	40%	sunflower oil	65	149	6	garnish sashimi	
coffee beans, whole	55%	unsalted butter	70	158	12	garnish sea urchin, shellfish, lemon risotto	4·371
garlic, thinly sliced	50%	olive oil	90	194	4	garnish pizza, roasted potatoes	
fresh ginger, thinly sliced	45%	sunflower oil	puree until smooth 70	158	3	garnish steamed fish	
Ibérico ham fat, thinly sliced	75%	olive oil	90	194	20 min	serve warm, blend into ham broth, garnish grilled peaches or watermelon	
langoustine (or other shellfish) shell, crushed to a fine paste and roasted	125%	unsalted butter	88	154	5	poach shellfish, blend into shellfish sauces	below
thyme leaves	20%	grapeseed oil	55	131	45 min	season cooked fish and shellfish, finish lemon risotto	
lemon zest, finely grated	45%	grapeseed oil	60	140	2	garnish salads and fish	
makrud (kaffir) lime leaf, sliced	15%	grapeseed oil	3	37	24	drizzle over grilled fish, brush on pork cutlets	next page
fresh mint, thinly sliced	16%	olive oil	80	176	1	mix into vinaigrette	
molasses **adapted from Michel Bras**	50%	unsalted butter	80 refrigerate for 4 d after cooking	176	20 min	fry sweetbreads or foie gras	331
dry porcini	50%	sunflower oil	70	158	1	blend into game broth	
rosemary	10%	olive oil	80	176	1	drizzle over roast lamb	
rose petal, untreated	80%	sweet apricot oil	55	131	1¼	make salad dressing, beurre blanc for fish	
truffle, minced	30%	unsalted butter	55 ultrasonic bath	131	1 15 min	garnish poached scallops or artichokes	

*(*set weight of fat to 100%*)

EXAMPLE RECIPE

SHELLFISH BUTTER

Yields 400 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Crustacean heads, bodies, and shells, finely crushed or ground	500 g	100%	① Vacuum seal together. ② Cook sous vide in 88 °C / 190 °F bath for 5 h.
Clarified unsalted butter	400 g	80%	③ Remove from bag, and cool at room temperature. ④ Refrigerate for 12 h. ⑤ Heat mixture to melt. ⑥ Strain; discard heads. ⑦ Decant butter. ⑧ Vacuum seal, and refrigerate until use.

(2009)

This recipe works with crab, crawfish, shrimp, prawn, and lobster of all varieties. It is a culinary classic that dates to traditional French cuisine.

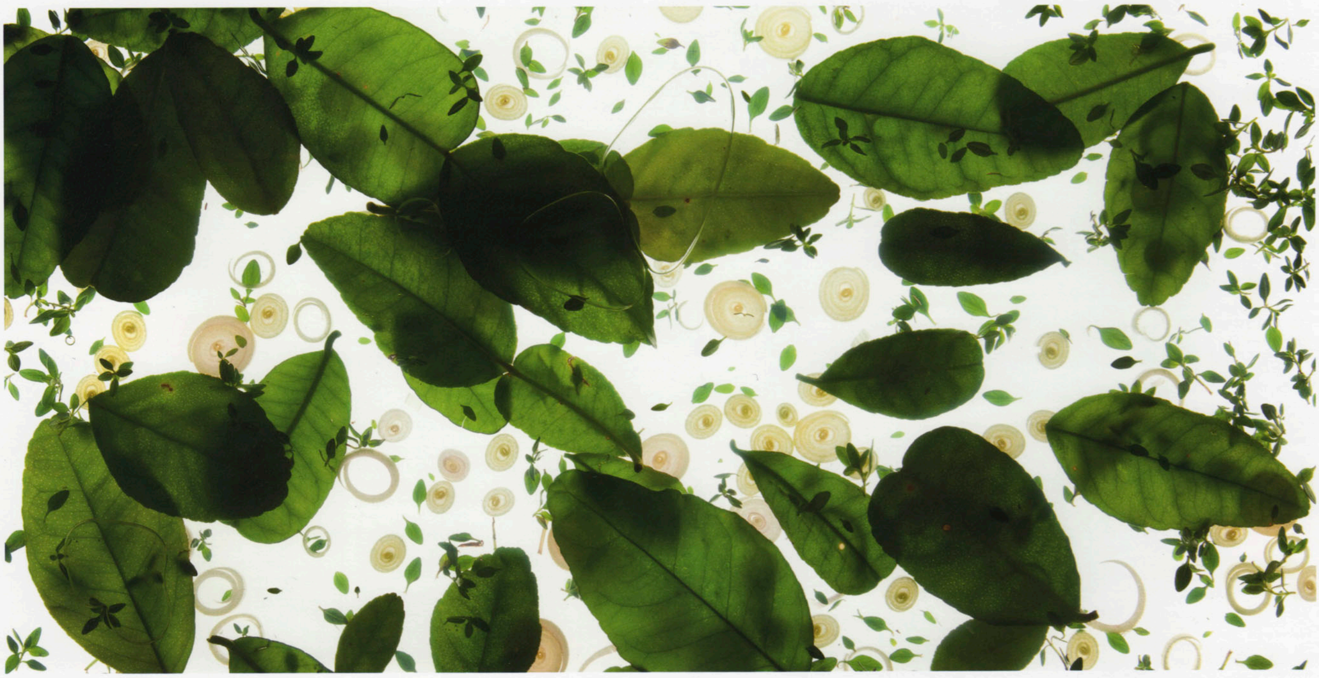
EXAMPLE RECIPE

SOUS VIDE LEMON HERB OIL

Yields 400 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Grapeseed oil	400 g	100%	① Combine.
Lemongrass, thinly sliced	80 g	20%	② Vacuum seal.
Lemon thyme leaves	50 g	12.5%	③ Cook sous vide in **60** °C / **140** °F bath for 1½ h.
Lemon balm leaves	20 g	5%	④ Chill and refrigerate for 12 h.
Makrud (kaffir) lime leaves	20 g	5%	⑤ Strain.
			⑥ Refrigerate until use.

(2010)



EXAMPLE RECIPE

SPICED CHILI OIL ADAPTED FROM JEAN-GEORGES VONGERICHTEN

Yields 1 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Grapeseed oil or other neutral oil	1 kg	100%	① Vacuum seal together. ② Cook sous vide in **70** °C / **158** °F bath for 24 h.
Chipotle chilies, thinly sliced	180 g	18%	③ Cool and refrigerate for 12 h. ④ Strain.
Coriander seeds, toasted and crushed	30 g	3%	⑤ Vacuum seal and refrigerate until use.
Mace, crushed	30 g	3%	
Dry red chilies, crushed	30 g	3%	
Star anise, crushed	30 g	3%	
Cinnamon sticks, toasted and crushed	20 g	2%	
Fennel seeds, toasted and crushed	12 g	1.2%	

(original 1997, adapted 2010)

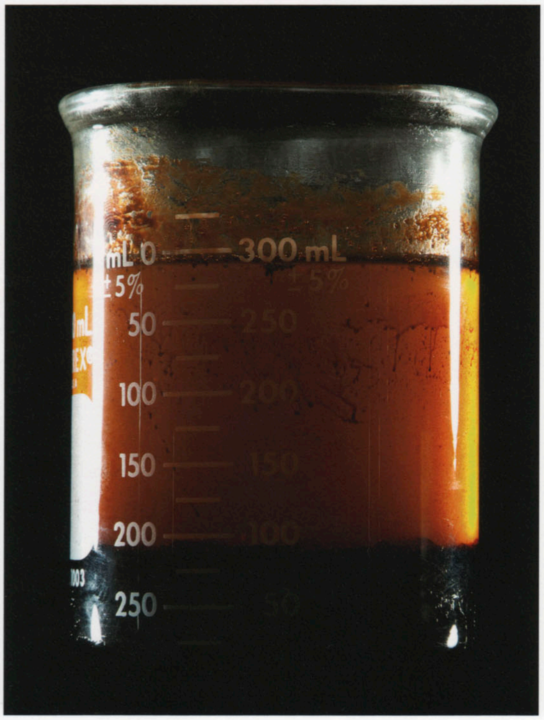
EXAMPLE RECIPE

MOLASSES BUTTER ADAPTED FROM MICHEL BRAS

Yields 200 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Unsalted butter, melted	200 g	200%	① Blend together.
Molasses	100 g	100%	② Transfer mixture to Mason jar, and seal.
			③ Place sealed Mason jar in 85 °C / 185 °F bath for 30 min.
			④ Remove jar from bath, and take off lid.
			⑤ Rest in jar at room temperature for 30 min to allow butter and molasses to separate.
			⑥ Pour butter into sealable container, and discard molasses.
			⑦ Seal, and refrigerate infused butter for 4 d.
			⑧ Decant butter, and refrigerate for use.

(published 2002)



EXAMPLE RECIPE

CURRY OIL ADAPTED FROM THOMAS KELLER

Yields 1 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Coriander seeds, toasted and crushed	90 g	9%	① Toast separately in small pans until just fragrant. ② Remove from heat.
Cinnamon stick, crushed	35 g	3.5%	
Canola oil or other neutral oil	1 kg	100%	③ Blend fully with toasted spices. ④ Vacuum seal.
Chaat masala see page 5·281	140 g	14%	⑤ Cook sous vide in 90 °C / 194 °F bath for 1 h.
Cayenne pepper	30 g	3%	⑥ Refrigerate for 12 h.
Mace	15 g	1.5%	⑦ Strain.
			⑧ Repackage, and refrigerate until use.

(published 1999, adapted 2010)

JUICING

Nothing is more fundamental to classic cuisine than making stocks. Chefs use the flavorful extracts of meats, fruits, and vegetables for everything from soups to sauces. But despite all the slicing, chopping, and simmering involved, stockmaking is a relatively gentle way to retrieve the flavor that plant and animal tissues have to offer. If you want the richest flavors, you need to do real violence to the biological building blocks of food in order to unlock the liquid essence within. That means rupturing cells—in other words, juicing.

The juice of a fruit, vegetable, or meat is water that is impure in the best of ways. This "dirty" water is loaded with sugars, soluble proteins, emulsified lipids and fat compounds, volatile aroma molecules, and other components that constitute a food source's portfolio of flavor and nutrients.

Cooks employ both brutish and more elegant ways to remove the juice from foods. In most commercial kitchens you can find a **Champion-style juicer**, based on a well-known product made by the Plastaket Manufacturing Company of Lodi California. You push food down a chute onto a serrated blade that is mounted on a horizontally rotating spindle. Whatever the spinning teeth of the blade rip into, be it cantaloupes or carrots, they shred the tissues to the very core. As cell walls rupture, the contents leak out and collect in a bowl. The specially designed contours of the spindle assembly meanwhile shunt the solid pulp into a receptacle.

Green Star is another brand of macerating juicer that is comparable with the Champion. Centrifugal juicers are made by many manufacturers of kitchen appliances.

This type of juicer processes food fast, but at some cost to the yield because a significant fraction of the juice remains in the pulp that is discarded. It has the advantage that it can juice things like wheat grass, which other juicers find difficult.

A **centrifugal-style juicer** can do better with some foods. Designed more like a blender or a food processor, a centrifugal machine pulverizes food that enters the juicing chamber with a flat cutting plate that sits at the bottom of a rapidly spinning mesh basket. The plate also flings the mashed pulp onto the perforated basket walls, where strong centrifugal forces drive the liquid out of the pulp and through the mesh. The juice finds its way out through a spigot into a waiting container.

Some centrifugal juicers are designed so that accumulating pulp is automatically pushed off the mesh basket and into a refuse bin. This handy feature lets you process more food before you must stop to clear caked pulp from the basket's sides.

Some cook use an even rougher option for juicing, one with roots that go back millennia: a **food press**. Cider makers and vintners know all about presses. A simple screw mechanism typically provides the mechanical leverage for squeezing food between flat plates. The plates themselves are designed so that they draw the extracted juice into a collection chamber that is positioned beneath the press assembly.

The **citrus press**, which has curved pressing surfaces to accommodate fruit halves, is perhaps the most familiar example of this class of machine. Even though presses can apply tremendous crushing forces, they tend to produce juice containing fewer particles than other kinds of juicers do because they compress food rather than tearing it.

But pressing can be tricky when you juice a food that simultaneously expels both desirable flavor components and chemical compounds that break down those same flavorants, a phenomenon that occurs most commonly with citrus fruits. Acids

Getting the juice out of food requires breaking open cellular structures. In doing so, numerous compounds mix together to create the fresh-squeezed flavor of the juice. But the flavor can be fleeting. Consider an orange: sugars, acids, and peel oils combine to create the unmistakable flavor of orange juice, but the acidity of the juice itself ultimately ruins the fresh flavor by destroying the aromatic peel oils over time.

10

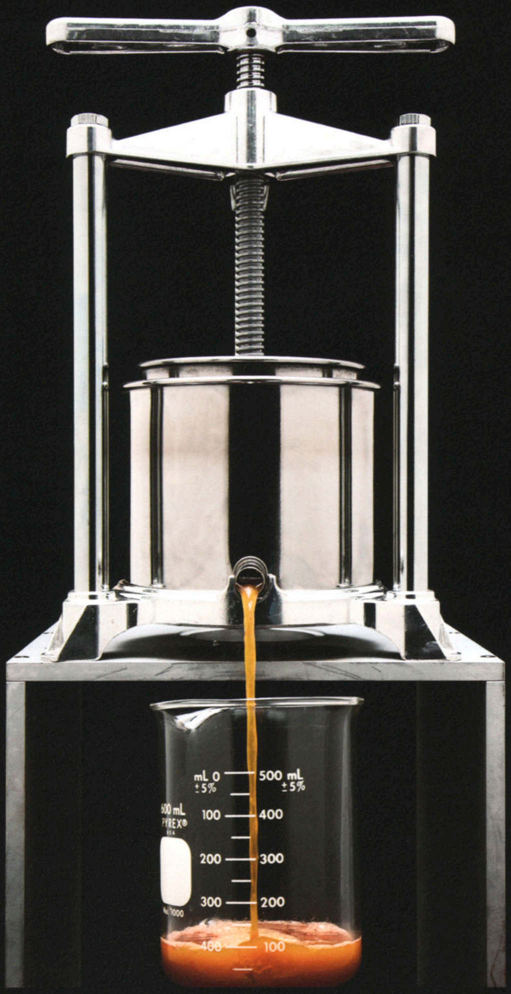
Juicer Designs

Champion-style juicer

This workhorse juicer, a common restaurant appliance, uses a serrated rotating blade to shred food, which enters the processing chamber though a port in the top. This type of machine rapidly removes and collects the juice while shunting residual pulp into a waste receptacle. The primary shortcoming of this juicer design is that the resulting pulp retains some liquid, which reduces the overall yield. A juicer of this style, however, is able to juice relatively dry foods like wheat grass that can be difficult for other juicers to process. Twin-gear juicers have a different internal mechanism but serve a similar role.

Centrifugal juicer

Reminiscent of a blender, this juicer design uses a broad, flat blade at the bottom of a spinning basket to both pulverize the food and fling it against the perforated sides of the basket. Centrifugal forces then expel most of the juice from the pulp. Unless the machine is designed to automatically clear the pulp deposits, the basket tends to clog quickly, requiring frequent manual cleaning.



Food press

A food press forces juice out mechanically by squeezing food between two hard, unyielding surfaces, once of which is perforated. Presses work best for softer foods; for hard foods, slight heating or adding sugar or enzymes is often used to soften the food enough to make pressing easier. In some presses, including cider presses, the food is placed between flat plates, often between multiple layers of plates. Citrus fruit presses generally pair convex and concave pressing surfaces to accommodate the approximately hemispherical shapes of orange, grapefruit, lemon, and lime halves.

that emerge during the process instantly begin to decompose the molecules in the fruit's essential oil that impart that characteristic citrus flavor. You should thus serve orange juice as soon after you squeeze it as possible, before these flavor-killing extracts can do too much damage.

Gentler Juicing Through Chemistry

Brawn and blades are not the only foundations for effective juicing. Chemistry works as well. You can add pectinase enzymes to fruit, for example, to break down the tough polysaccharides in the plant cell walls. Treating even hard-textured fruits such as apples, pears, or pineapple with pectinase will make them go soft, thus boosting the juice yield.

Enzyme treatments also work on meats. Apply the proteolytic enzyme bromolain (a naturally occurring component of pineapple juice) to the meat before you press it to double the yield of natural juices extracted.

Another gentle juicing tactic suggested by chemistry works by drawing the juices out of the food by exploiting a phenomenon known as **osmosis**. Think of osmosis as the chemical version of water seeking its own level. If very salty water is adjacent to less salty water and a permeable barrier of some kind prevents the salt molecules from moving freely, the water molecules try to even things up by diffusing through the barrier from the less salty side to the saltier side until the two solutions are equally salty. It is as if there were a pressure pushing on the solution with the higher concentration of water molecules (and thus the lower concentration of salt)—and in fact scientists do talk about the **osmotic pressure** created by a difference in concentrations between adjacent solutions. Osmosis works for any liquid medium and any dissolved compound, not just water and salt.

Juicing by osmosis can be as straightforward as sprinkling sugar on a cut lemon or scattering salt onto slices of cabbage or eggplant. Before long, some of the juice inside the cells migrates across the cell walls and starts to accumulate around the fruit or vegetable, and it can easily be collected. This juicing method is most useful when you are preparing very salty dishes, such as sauerkraut (see page 3·351), or very sweet juices for a sorbet or fruit coulis.

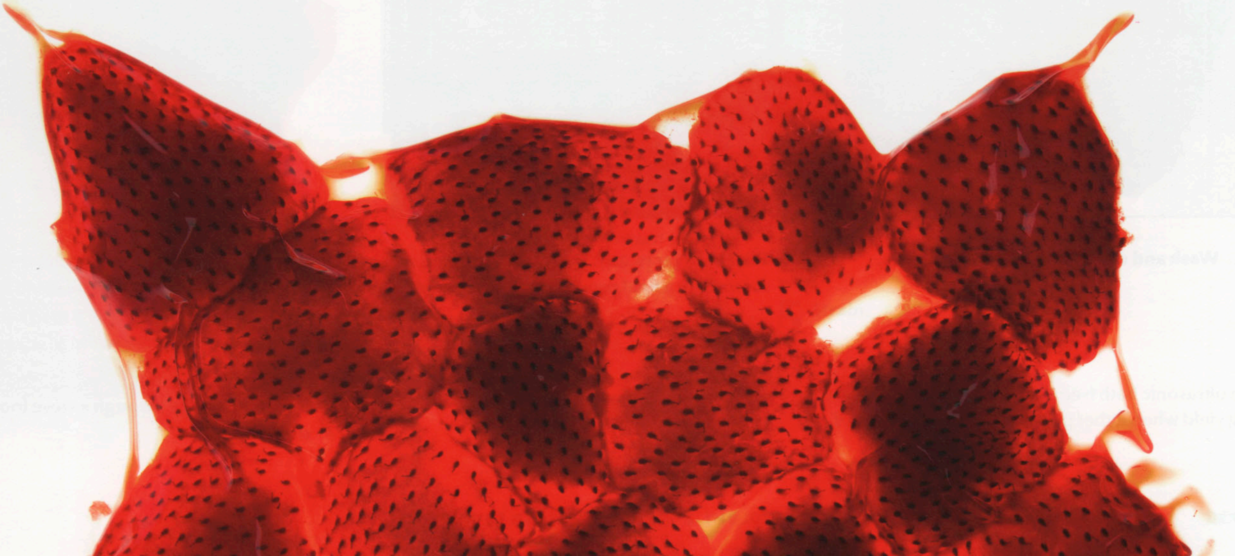
Squeezing by Ice and Fire

When a fruit freezes, minuscule dagger-like ice crystals form inside, puncturing the cell walls. As the ice crystals grow, they force sugars, flavor compounds, and other juice components into the remaining liquid juice, which lowers the freezing point of the sweetened juice. So if you freeze the fruit, then thaw it, highly concentrated juice emerges first; less concentrated juice follows as the crystals of ice melt. This approach is very well suited for juicing sweet fruits, such as raspberries and blueberries.

Enzymes are catalysts, chemicals that speed reactions (often by huge factors) without themselves being used up in the process. When the precursor molecules in a flavor reaction run out, there are still plenty of enzymes left.

Small, tasty molecules such as sugar and salt work best at drawing juices out of food. Larger molecules such as starch do not have the same osmotic effect.

Freezing is one of our favorite methods for concentrating flavors. For more details, see Freezing Out the Good Stuff, page 396.



JUICING STRATEGIES

HOW TO Extract Juice From Plants with Pectinase

Enzymes can cleave the compounds that glue together the walls of plant cells, softening fruits and vegetables and thus freeing them to express their juices. It may be time-consuming to macerate fruits or vegetables in a solution of naturally occurring enzymes such as pectinase, but this approach avoids some of the problems that occur when foods are juiced mechanically, such as browning, cloudiness, and bitterness. The assistance of pectinase is particularly helpful for removing juice from tougher plant foods, such as apples, pears, and carrots. The enzymatic treatment dramatically improves juice yields.

1 **Peel the fruit and vegetable.**

2 **Puncture the skin with needles (optional).** The perforation will accelerate the infusion of the solution and thus speed extraction.

3 **Add pectinase enzymes to water at the concentration recommended by the manufacturer.**

4 **Vacuum seal the food with the enzymatic solution.** Use as little water as possible to avoid diluting the juice.

5 **Refrigerate until the juice has been expressed.** Several hours to several days of chilling may be required, depending on the size and the durability of the fruits or vegetables. For faster results, warm the bag in a water bath at a temperature below 50 °C / 122 °F for up to 4 h.

6 **Strain, pressing lightly on the solids to yield more juices.**

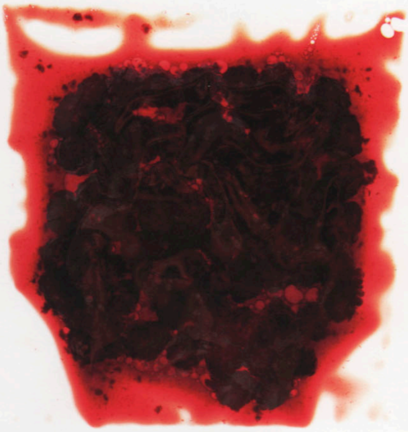
HOW TO Extract Juice by Osmosis

Dissolving sugar in the small amount of water on the surface of a fruit or vegetable will create a solution concentrated enough to pull the abundant, flavor-laden liquid from inside its cells to the outside.

Salt has the same effect and may be more appetizing for certain vegetables. A good way to accelerate the osmosis process is to cut the food into smaller pieces.

1 **Wash and dry fruit or vegetable pieces.**

2 **Coat in sugar or salt.** Use glucose instead of sucrose for a final product that is less sweet.



3 **Warm for a few hours to extract the juice.** Optionally, vacuum-seal and place in warm water bath. Higher temperatures, up to 60 °C / 140 °F, will speed the process.

4 **Decant the juice through a sieve (not shown).**

An ultrasonic bath (see page 415) is helpful for increasing yield when either pectinase or osmosis is used.

HOW TO Extract Juice By Freezing

Freezing may seem like a passive approach compared with pressing or pulverizing the food, but it can actually yield more juice and more intensely flavored, deeply colored liquid, than mechanical approaches alone. The process exploits the power of ice crystals to rupture cells. After thawing, the cells give up their juices with little effort.

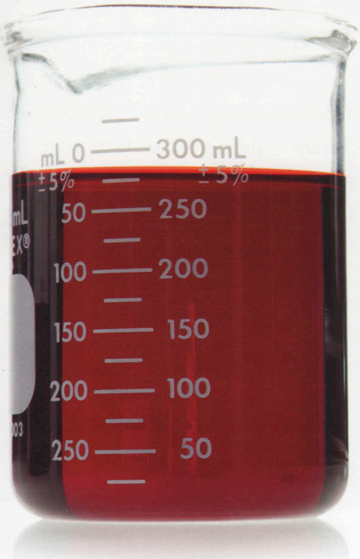
1 **Seal food in freezer bag.** This approach works particularly well for berries, such as blueberries or raspberries.

2 **Freeze for as long as possible.** It's ideal to store summer berries into the winter. Long-term frozen storage with periodic freeze–thaw cycles produces the largest ice crystals.

3 **Thaw (not shown).**

4 **Juice.**

5 **Strain.**



Juicing Strategies

It's one thing to extract an intensely flavored juice, but it's quite another to keep that juice fresh and appetizing until it reaches the table. The cellular destruction that occurs during juicing both helps and hinders freshness. Many of the flavors we like in fresh juice form only as the cells fall apart, flavor-creating enzymes that previously had been locked inside cells. But the tissue damage also sometimes releases destructive enzymes that wreak havoc on flavor, aroma, and pigment compounds.

The distinctive aroma of onions, garlic, and cabbage, for example, come into being only as a result of enzymatic transformations that occur when the cell walls are ruptured. The same is true of the characteristic flavors of fruits like strawberries and tomatoes. Because enzymatic reactions occur over time, the flavor of some foods, say, a ripe strawberry, is the result of rapidly changing concentrations of various enzymatically created aromas.

The sometimes dramatic evolution of flavors over short periods of time helps explain why no one has yet found a way to artificially replicate true strawberry flavor and capture it in a bottle. For many foods, the flavor of an essence is akin to playing its entire symphony of flavor notes all at once, rather than releasing the sequence of individually orchestrated molecular interactions that underpin the food's real flavor profile.

The moment that the supply of precursor molecules runs dry, however, the enzymatic flavor-making chemistry shuts down. And all too soon, the less stable flavor compounds start to break down. True freshness is fleeting indeed.

One simple way to extend the freshness window of some juices is to add a little freshly squeezed juice. This strategy provides fresh material for the enzymes, inducing them to unlock a new wave of flavor. A few just-juiced strawberries will, for example, renew a bowl of leftover strawberry juice that's been sitting in the fridge.

Although sulfites are widely used as preservatives in the food industry, some people are unable to tolerate even small quantities of them (see page 1·238).

Another challenge that comes with juicing is the reality that many juices brown fast. Just as a hard punch in the eye soon produces a black and blue shiner, trauma to plant tissues can turn them brown. Being run through a juicer counts as a highly traumatic event.

Browning is actually a defense mechanism. If a plant gets scratched, smacked, or otherwise injured, it becomes vulnerable to infection. To defend against germs, it raises antimicrobial defenses. In particular, the tissue releases the enzyme **polyphenol oxidase**, or PPO, which leads to the production of protective compounds such as tannins and to brown color.

To prevent discoloration, therefore, one strategy is to restrain the activity of PPO. You can destroy PPO with heat, but even at a boil this can take minutes and is enough to wreck some of the fresh aromas. Chilling the juice, in contrast, slows the browning almost immediately because enzymatic reactions slow down drastically as the temperature drops.

You also need to worry about the pulp, where the concentrations of oxidizing enzymes and their molecular targets are much higher. The pulp usually browns long before the juice changes color. Pigments derived from PPO are soluble in water, so they slip right into the juice. Straining out the pulp as completely as possible before it has a chance to discolor the juice will preserve the fresh color of the juice.

The practical implications of all this are pretty straightforward: keep the food you are juicing as cold as is practical, and strain the pulp out promptly. To further slow browning and the formation of unwanted pigments, add antioxidants such as vitamin C (ascorbic acid) if the acidic taste will not be too disruptive. Or add more neutral-tasting and potent preservatives such as sulfites (used widely in winemaking) or sodium benzoate.

HOW TO Keep Fresh-Squeezed Juice Fresh

Making fresh juice is time-consuming, hard work, so you'll want to take steps to preserve the bright color and intense flavor that make fresh-squeezed juice incomparably better than pasteurized, bottled, or frozen juice. The seven general strategies below, individually or in combination, will help.

1 **Keep everything cold.** Browning is caused by enzymes that respond dramatically to heat: for every 10 °C / 18 °F drop in temperature, enzymatic activity falls by about half. You can safely chill most fruits and vegetables to just above freezing before juicing them. Tropical and subtropical produce—including bananas, mangoes, avocados, strawberries, and tomatoes—should never be chilled before juicing.

2 **Freeze before juicing.** If preservation is more important than purity of flavor, try storing the food at −18 °C / 0 °F or colder for several days. For many plant foods, the deep freeze will permanently destroy browning enzymes—albeit with some collateral damage to flavor-creating enzymes.

3 **Blanch before juicing.** A three-minute dip in boiling water (or 5 min at 94 °C / 201 °F) destroys browning enzymes. Unfortunately, the required temperatures are so high that some plant foods will partially cook by the time the enzymes break down.

4 **Filter our the pulp.** It takes two to brown, and without the pulp present, the enzymes have no tissue to act on to form the brown pigments that discolor the juice.

5 **Lower the pH.** The more acidic the juice, the slower the enzymatic reactions that cause discoloration. High acidity also acts directly on brown pigments to lighten their color. Unfortunately, low pH is damaging to the fresh flavor of citrus juices.

6 **Get the air out.** Oxygen is essential to the activity of the various enzymes that discolor juice. Vacuum sealing the juice will help to slow browning but will not halt it because some oxygen is dissolved in the juice itself.

7 **Add a preservative.** The ingredients listed in the table below inhibit browning or preserve flavor through a variety of mechanisms. They can be used solo but typically work better in combination. This is often the best strategy.

Additives to Preserve the Color and Flavor of Fresh Juice

Function	Ingredient	(scaling)	Note
inhibits browning, preserves color	ascorbic acid (vitamin C)	0.1%–0.3%	works best with citric acid
	citric acid	0.5%–2.0%	these fruit acids interfere with browning enzymes directly and by lowering pH; they work best in conjunction with ascorbic acid
	malic acid		
	tartaric acid		
	oxalic acid		
	honey	10% or more	High concentrations have preservative effects.
	sodium benzoate	0.05%–0.1%	use only for foods with a pH ≤ 4.5; maximum permitted quantity is 0.1%; slows both browning and bacterial and fungal growth
	sodium metabisulfite (Campden tablets)	0.01%–0.05%	most effective at 0.03%; unpleasant flavor above 0.05%
restores or preserves flavor	fresh juice	5%–10%	add just-squeezed juice before serving to produce fresh volatile aromatics that refresh the flavor in some juices
	essential oil	0.001%–1%	add a few drops of the appropriate citrus essential oil just before serving to replenish natural oils from the peel and restore fresh flavor
	alpha tocopherol (vitamin E)	0.025%–0.05%	antioxidants such as vitamin C and vitamin E help protect aromas from the ravages of oxidation

EXAMPLE RECIPE

MEYER LEMONADE

Yields 325 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Meyer lemon juice	300 g	100%	① Centrifuge at 27,500*g* for 1 h. ② Decant juice and strain through fine sieve.
Fructose	30 g	10%	③ Whisk into clarified juice until dissolved and reserve.
Citric acid	1.5 g	0.5%	
Gum arabic	5 g	1.7%	④ Blend together until fully emulsified.
Water	2 g	1%	⑤ Add 1.5 g of emulsion to sweetened juice.
Lemon essential oil	0.12 g (seven drops)	0.04%	⑥ Hand-blend until smooth.
			⑦ Strain through fine sieve.
			⑧ Chill before serving.

(2010)

Always add the essential oil just before serving. The acidity of the juice will destroy the essence. This is why the best quality citrus oils are made by removing the peel before cold pressing so there is no chance for the acidic fruit juice to damage the peel oil.

EXAMPLE RECIPE

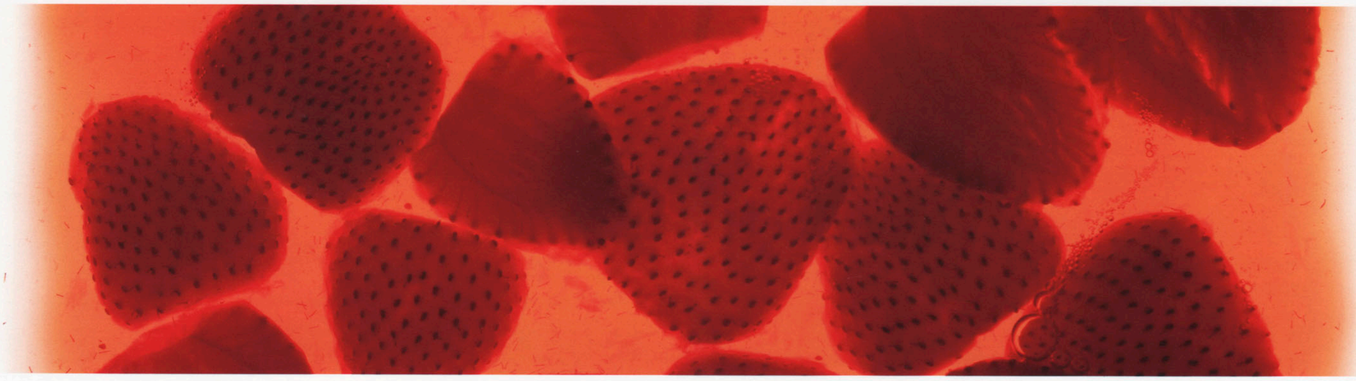
SOUS VIDE BERRY JUICE

Yields 50 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Blackberries (fresh)	100 g	100%	① Combine.
Sugar	7 g	7%	② Vacuum seal sweetened berry mixture.
Isomalt	5 g	5%	③ Cook sous vide in 65 °C / 149 °F bath for 1 h.
			④ Remove from bag, and cool at room temperature.
			⑤ Strain through fine sieve; discard pulp.
			⑥ Chill before serving.

(2010)

This process works equally well for blueberries, raspberries, and strawberries.



EXAMPLE RECIPE

MELON WATER

Yields 100 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Melon juice	100 g (from 200 g of melon)	100%	① Whisk together and season to taste. ② Centrifuge at 27,500*g* for 1 h. ③ Decant only clear juice. ④ Vacuum seal, and refrigerate until use.
Fructose	5 g	5%	
Lime juice	2.5 g	2.5%	
Tartaric acid	0.5 g	0.5%	
Salt	to taste		

(2009)

The flavor of melon is created by enzymatic reactions during juicing. The fresh flavor can be reinvigorated by adding a small amount of fresh melon juice to the batch just before to serving.

EXAMPLE RECIPE

GREEN ASPARAGUS AND MORELS WITH ASPARAGUS JUS

ADAPTED FROM JEAN-GEORGES VONGERICHTEN

Yields 650 g (four portions)

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Pencil green asparagus, unpeeled	200 g	80%	① Juice with Champion-style juicer. ② Measure 50 g for recipe.
Asparagus juice, from above	50 g	20%	③ Whisk ascorbic acid immediately into fresh juice to prevent browning. ④ Vacuum seal.
Ascorbic acid	0.4 g	0.16% *(0.8%)**	⑤ Refrigerate.
Jumbo green asparagus, stalks peeled	250 g (eight stalks)	100%	⑥ Sauté for 3 min on all sides until just tender and golden. ⑦ Remove from heat, and reserve.
Clarified unsalted butter see page 4·213	25 g	10%	
Jumbo green asparagus, stalks peeled	250 g (eight stalks)	100%	⑧ Vacuum seal. ⑨ Cook sous vide in 85 °C / 185 °F bath for 12 min, immediately remove from bag, and reserve.
Clarified unsalted butter	25 g	10%	
Morels, thoroughly washed	120 g	48%	⑩ Meanwhile, sweat together for 5 min until tender and just cooked through.
Unsalted butter	50 g	20%	
Shallot, finely minced	30 g	12%	
Vin jaune (or Fino sherry)	25 g	10%	⑪ Add to morels, and cook for 3 min.
Heavy cream	15 g	6%	
Instant hollandaise see page 4·228	80 g	32%	⑫ Warm to 65 °C / 149 °F. ⑬ Dispense from siphon, and fold into morels. ⑭ Set aside, and keep warm.
Asparagus puree see page 424	50 g	20%	⑮ Warm prepared asparagus juice over medium heat. ⑯ Whisk in puree.
Unsalted butter	10 g	4%	⑰ Whisk into warm thickened jus until fully emulsified.
Lime juice	to taste		⑱ Season jus.
Salt	to taste		
Flaky sea salt	to taste		⑲ Reheat reserved asparagus stalks. ⑳ Season. ㉑ Place two sous vide cooked stalks and two pan fried stalks in center of each plate.
Chive blossoms (or finely minced chives)	10 g	4%	㉒ Garnish with warm morels and blossoms. ㉓ Pour jus around plates at table.

(original 1997, adapted 2010)

(% of total weight of asparagus juice)

Jus, not Stock

Despite their central role in commercial kitchens, meat stocks are in reality something of a cheat. Stocks were developed as substitutes for an even more fundamental and desirable essence of cooked meat: its juice, or jus.

Cooking meat causes collagen to shrink, which makes the meat squeeze itself to the point that juice leaks from it. To make jus, you want to create flavors within the roasting meat, then extract them. Meat *jus* is the liquid component of the cooked flesh that has been separated from the solid parts. When you roast a chicken, steak, or leg of lamb, you can usually coax out a few tablespoons of jus just by pressing on the cooked meat. But that's just too little jus to be practical for the saucing needs of a busy kitchen.

The main advantage of a stock in which flavor is pulled from meat and vegetables using slow heat and water, is that it secures a substantial portion of the flavor that jus provides without the need to roast lots of animals. Stocks simply cost less to make than jus does, and they yield much larger quantities.

A stock does not taste like a jus, however, because the two contain different molecular ingredients. Analyze the composition of a jus, and you'll find countless cellular constituents that saturate the water in meat, among them large protein molecules, savory peptides, and amino acids, sugars, salts, and myriad oily compounds, including lipids and fatty acids.

You'll also find a rich ensemble of flavor compounds in jus that form by a complex sequence of heat-driven chemical reactions called **Maillard reactions**. These chemical transformations, first described by the French chemist Louis Camille Maillard in 1912, occur when you heat at high temperature a mixture of certain sugars and amino acids. The Maillard reactions constitute an important nonenzymatic browning process that is largely responsible for the meaty aromas of roasting.

Small changes in the temperature or moisture content at the meat's surface can dramatically favor one or another of the many reaction pathways that are possible during cooking. This fact helps explain why boiled meat, roasted meat, and fried meat all taste different. As the meats cook, each method of cooking causes different sets of chemical reactions to prevail. These reaction generate many of the volatile compounds that distinguish the flavor of boiled beef from that of a roasted lamb or a fried chicken.

Unlike boiled meat in a stock, roasting meat browns on its surface. The jus forms primarily in the hotter and drier regions, which are reaction zones where watery liquids emerge from inside and then evaporate, leaving a concentrated residue of oily and intensely flavored jus to drip into the pan below.

Water wicks from the interior of the meat to its surface, carrying with it new raw materials that feed the ongoing flavor-generating reactions. But because of Fick's law—the rules governing diffusion of flavor compounds described previously in Extracting Flavors—no more than 20% or so of the water in a roast migrates to the surface to supply compounds for these reactions. So you never get a whole lot of jus, but the little you do get is almost ethereal in nature.

For more on Maillard reactions, see page 3·89.

In everyday home cooking, you can typically harvest enough jus from a roast chicken or leg of lamb—some of it as classic, superconcentrated fond, otherwise known as pan scrapings—to prepare enough gravy or soup for the dinner table. But busy commercial kitchens must settle for an approximation of jus; stocks represent the only practical and affordable means to produce rich cooking bases in sufficient volume to meet the desires of the diners and the needs of the market.

Squeezing in cheesecloth is a traditional way to wring juice from food.

PARAMETRIC RECIPE

JUS

Jus (pronounced "zhew" in French) means juice. It refers to a simple sauce made from the natural juices that escape from foods—usually meats—as they cook. To make a jus, you collect those juices and skim off the fat. An unadulterated jus makes a highly flavorful accompaniment for roasted meats.

Unfortunately, natural jus is a precious commodity because you sacrifice the quality of the source food to make it. But you can sometimes collect jus by pressing and sieving trimmed portions that are not meant to be served and thereby avoid cooking valuable meat just for its jus. Reducing a stock to yield a more concentrated, seasoned liquid creates something that mimics jus but isn't the same.

Modernist tools such as sous vide equipment and pressure cookers—as well as ingredients such as proteolytic enzymes—makes it easy to make good, natural jus with less fuss and waste. The table below lists several ways to create a thicker mouth-feel and viscosity; effects on the flavor and yield vary by strategy.

Best Bets for Jus

Recipe	Liquid	(scaling)	Protein	(scaling)	Aromatic	(scaling)
beef juice	n/a		ground beef	100%	n/a	
beef jus	brown beef stock	100%	ground beef	35%	carrot, thinly sliced	12%
	red wine	30%	oxtail, jointed	15%	onion, thinly sliced	10%
chicken juice	n/a		ground chicken	100%	n/a	
brown chicken jus	brown chicken stock	100%	ground chicken wing	15%	shallot, thinly sliced	20%
	chicken juice (from above)	40%	chicken foot	8%	dried morel	5.0%
	fino sherry	20%			thyme	0.1%
mushroom jus	mushroom stock	100%	n/a		crimini mushroom, thinly sliced	75%
	fino sherry	20%			shallot, thinly sliced	20%
	white port	10%			white miso	7.0%
	tamari	1%			thyme	0.1%
mussel jus	white wine	10%	mussels	100%	shallot	10%
					bay leaf	0.01%
pork and Banyuls roasting jus	brown pork stock	100%	ground pork shoulder	75%	sweet onion, thinly sliced	8%
	Banyuls wine	25%	ground pork trotter skin and meat	10%	carrot, thinly sliced	7%
rare beef jus	water	5%	beef, cubed	100%	n/a	
rare salmon jus	water	5%	salmon fillet, cubed	100%	n/a	
shellfish jus	shellfish stock	40%	shellfish heads	100%	tarragon extract	1.5%
	white wine	38%			white pepper	to taste
	vermouth	13%				
vegetable jus	onion juice, clarified	100%	n/a		n/a	
	carrot juice, clarified	80%				
	celery juice, clarified	55%				
	leek juice, clarified	30%				

	Cook					
Method	(bar)	(psi)	(°C)	(°F)	(h)	See page
cook sous vide			90	194	1½	349
pressure cook	1	15			1½	
cook sous vide			90	194	1	349
brown meat and bones, pressure cook	1	15			1	
pressure cook	1	15			25 min	348
cook sous vide			100	212	4 min	next page
brown meat and bones, pressure cook	1	15			1½	5·17
cook sous vide			53	127	4	349
cook sous vide			50	122	1	5·161
cook sous vide			88	190	1½	347
cook sous vide			85	185	3	

MAKING JUS

1 **Select a recipe (on the previous page).** The table Best Bets for Jus below lists several possibilities.

2 **Vacuum seal the liquids, proteins, and aromatics together.** Quantities are proportional to whichever ingredient (usually the protein or the stock) is set to 100%. For example, use 38 g of wine and 13 g of vermouth for every 100 g of heads when making shellfish jus.

3 **Cook.** Recommended cooking methods, temperatures, and times are indicated in the table.

4 **Press, strain, or sieve.**

5 **Season.** For seasoning options, see Best Bets for Lowering pH on page 314, Seasoning with Salt and Other Flavor Enhancers on page 312, and Best Bets for Adding Flavor with Alcohol on page 317.

THICKENING STRATEGIES FOR SAUCES, JUS, AND GLAZES

Strategy	Heat	Speed	Yield	Note	Uses	See page
reduce on stove top	high	fast	low	high heat strips away volatiles	redeye gravy	5·101
					brown beef jus	
					garlic jus in a jar	348
reduce by vacuum evaporation	low	moderate	low	more vibrant flavor after reduction	pork Banyuls jus	5·19
					osso buco glaze	5·60
					apple and cabbage juice	389
concentrate with agar	high	fast	low	the amount of liquid that weeps from the gel determines the intensity	fruit juices	372
concentrate by freezing	low	slow	low	best bet for many liquids; yields an intense, vibrant flavor	mushroom jus	348
					shellfish jus	below
					mandarin juice	3·356
thicken with fat (emulsification)	n/a	fast	high	rich mouthfeel and a flavor that varies with the kind of fat used; diminishes the intensity of flavors	sauce américaine	5·184
					constructed veal cream	5·31
					jus gras	5·113
					prawn jus	347
					smoked salmon jus	
thicken with fluid gel	varies	moderate	high	vibrant flavor; suitable only for liquids that tolerate cooking; good for thicker sauces	tajine glaze	
					pot-au-feu jus	5·49
thicken with gum	usually not required	fast	high	best bet for raw juices and thin sauces	salmis sauce	5·125
					rare beef jus	349
					jus de roti	4·54
					rare salmon jus	5·161
					truffle jus	4·53
thicken with pregelatinized starch	n/a	fast	high	good strategy for raw juices and thin sauces; diminishes the intensity of flavors	garum jus	5·107
					rare salmon jus	
					sous vide vegetable jus	

EXAMPLE RECIPE

SOUS VIDE MUSSEL JUICE

Yields 100 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Mussels, rinsed thoroughly with beards removed	1 kg	100%	① Vacuum seal in one even layer. ② Steam for 4 min. ③ Shock in ice-water bath. ④ Shuck, and reserve meat for another use. ⑤ Strain rendered mussel juices from bag and shells. ⑥ Vacuum seal and refrigerate until use.

(2010)

Mussel juice is classically used to accentuate the flavor of seafood broths and sauces. This sous vide method extracts the juices from the mussels without overcooking them so the meat can be used as a garnish for cooked fish (see page 5·151). Inspect mussels carefully and discard any dead or sandy shellfish. These can spoil the juice.

EXAMPLE RECIPE

JUS DE LA PRESSE INSPIRED BY ALAIN DUCASSE

Yields 350 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Lobster heads	600 g (about four heads)	100%	① Sauté until shells are golden and very aromatic, about 10 min. ② Baste constantly with butter to cook through.
Clarified unsalted butter	60 g	10%	③ Place heads in basket of wine press. ④ Extract juices by crushing shells completely with wine press.
White wine (dry)	200 g	33%	⑤ Combine with extracted lobster juices.
Lobster stock see page 296	120 g	20%	⑥ Reduce lobster juice by half.
Cognac	30 g	5%	
Lobster roe	80 g	13%	⑦ Blend with warm reduction until fully emulsified.
Unsalted butter	80 g	13%	
Olive oil	35 g	6%	
Lemon juice	to taste		⑧ Season.
Salt	to taste		

(published 2001, adapted 2010)

EXAMPLE RECIPE

SOUS VIDE VEGETABLE JUS

Yields 750 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Yellow onions, thinly sliced	400 g	100%	① Prepare vegetables as noted.
Carrot, peeled and thinly sliced	270 g	67.5%	② Combine, and vacuum seal. ③ Cook sous vide in 85 °C / 185 °F bath for 3 h.
Water	160 g	40%	④ Strain through fine sieve, and cool.
Celery, peeled and thinly sliced	120 g	30%	
Leek, white only, thinly sliced	120 g (from 275 g peeled leeks)	30%	
Unsalted butter, cubed	45 g	11%	⑤ To serve, heat stock to 85 °C / 185 °F. ⑥ Blend in butter until fully emulsified.
Lemon juice	to taste		⑦ Season.
Salt	to taste		

(2010)

EXAMPLE RECIPE

SOUS VIDE PRAWN JUS

Yields 250 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Prawn heads	400 g	100%	① Combine.
Shellfish stock see page 296	160 g	40%	② Grind coarsely in food processor. ③ Vacuum seal.
Vermouth (dry)	80 g	20%	④ Cook sous vide in 88 °C / 190 °F bath for 1½ h. ⑤ Strain through fine sieve.
Tarragon extract see page 310	6 g	1.5%	⑥ Whisk in.
Salt	to taste		⑦ Season.
White pepper	to taste		

(2010)

Shellfish butter (see page 329) is the product of a very different approach to extracting flavor than the one used here. Try both approaches to see what each one offers.

EXAMPLE RECIPE

LAMB GARLIC JUS IN A JAR

Yields 300 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Lamb trim, ground	1 kg	100%	① Pan fry ground lamb until golden.
Frying oil	90 g	9%	② Reserve meat and 10 g of rendered fat.
Carrots, peeled and thinly sliced	300 g	30%	③ Prepare vegetables as noted. ④ Sauté together in saucepan with reserved lamb fat, until tender.
Shallots, thinly sliced	200 g	20%	
Sweet onions, thinly sliced	150 g	15%	
Fennel, thinly sliced	125 g	12.5%	
Garlic, peeled and thinly sliced	50 g	5%	
Red bell pepper, thinly sliced	50 g	5%	
Tomato paste	25 g	2.5%	⑤ Add to vegetables, and increase heat to high.
Star anise, crushed	3 g	0.3%	⑥ Stir mixture continuously until golden brown and fragrant, about 3 min.
Water	500 g	50%	⑦ Deglaze pot, and stir in browned meat.
White wine	200 g	20%	⑧ Remove from heat.
Thyme	5 g	0.5%	⑨ Divide mixture equally between two Mason jars.
Bay leaf	2 g	0.2%	⑩ Seal jars, and place on rack in pressure cooker.
			⑪ Fill cooker with water to cover bottom 2.5 cm / 1 in of jars.
			⑫ Pressure-cook at a gauge pressure of 1 bar / 15 psi for 1½ h.
			⑬ Remove jars from cooker, remove lids, and cool jus to room temperature.
Lemon juice	to taste		⑭ Strain stock.
Salt	to taste		⑮ Reduce strained stock until thickened, about 12 min, and season.

(2009)

EXAMPLE RECIPE

MUSHROOM JUS

Yields 270 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Crimini mushrooms, thinly sliced	150 g	60%	① Sauté mushrooms and shallots together in butter until deep golden brown, about 12 min.
Shallots, thinly sliced	40 g	16%	
Clarified unsalted butter	25 g	10%	
Mushroom stock see page 296	200 g	80%	② Combine with cooked mushroom mixture in pressure cooker.
Fino sherry	40 g	16%	③ Pressure-cook at a gauge pressure of 1 bar / 15 psi for 25 min.
White port (dry)	20 g	8%	④ Strain through fine sieve, and discard solids.
			⑤ Measure 250 g of mushroom jus.
Mushroom jus, from above	250 g	100%	⑥ Blend together until dissolved.
White miso	14 g	5.6%	⑦ Strain.
Tamari soy sauce	2 g	0.8%	
Thyme	2 g	0.8%	
Konjac gum	0.75 g	0.3%	
Salt	to taste		⑧ Season.
Sherry vinegar	to taste		

(2010)

To make canned juice, use a pressure canner and vent for 10 min.

For juicing methods, see page 338.

This mushroom jus is richer and more full-flavored than a simple mushroom stock. It is important to stir the konjac gum continuously for a few minutes to ensure that it is fully hydrated and that no clumps form.

EXAMPLE RECIPE

SOUS VIDE RARE BEEF JUS

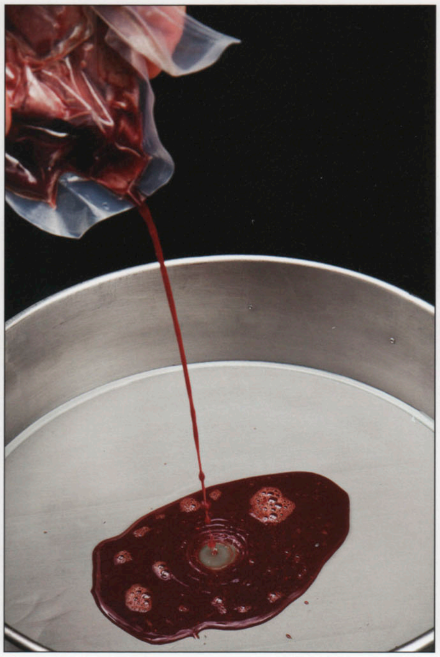
Yields 350 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Beef (preferably a tough cut)	1 kg	100%	① Cut into 1 cm / ½ in cubes.
Bromelain powder (optional, NOW brand)	2 g	0.2%	② Combine meat and bromelain (optional) ③ Cook sous vide in 53 °C / 128 °F bath for 4 h. ④ Strain rendered juices through fine sieve, and measure 300 g of juice.
Water	50 g	5%	⑤ Combine with juice.
Salt	to taste		⑥ Season.
Sherry vinegar	to taste		⑦ Vacuum seal, and refrigerate. Do not reheat above 53 °C / 127 °F, or jus will coagulate.

(2010)

Rare beef jus created this way can be used for many purposes. Tougher meats may require more time to release their juice.

3



4a

4b

EXAMPLE RECIPE

SOUS VIDE BEEF JUICE

Yields 300 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Ground lean beef	1 kg	100%	① Vacuum seal. ② Cook sous vide in 90 °C / 194 °F bath for 1½ h. ③ Strain juice, and discard meat. ④ Cool juice completely. ⑤ Vacuum seal, and refrigerate until use.

(2010)

This process can be applied to all types of meats. Using the resulting juice, although more costly than water, is a more flavorful alternative than using water to make broths and sauces.

FILTERING

Much of what goes on in a kitchen revolves around separating the components of mixtures. When a cook pours a pot of pasta into a colander, the water runs out through the holes as the colander retains the steaming pasta. When a winemaker removes yeast particles from wine, the segregation process is more involved, requiring a filtration system that pumps the wine through a series of cellulose pads that trap the solids.

Cooks use separation techniques to make food smoother, clearer, cleaner, less gritty, and otherwise finer in some way. Often they want to eliminate certain components in the mix to refine a dish's flavor or to adjust its texture and mouthfeel. In the case of soup, straining out solid particles that are larger than the tongue can discriminate—about 7 microns, a mere 0.0003 inch, in size—smooths out the broth. And cooks regularly remove selected elements from a dish to improve its appearance—recognizing, for example, that diners prefer a clear broth to a turbid one.

All methods of filtering segregate solid particles from the liquids in which they are suspended. Filters fall along a spectrum defined by the size of the particles they can remove. The smaller the pore size of the filter, the more pressure you must apply to force the liquid through the porous media. There is a whole toolbox full of filtering methods available to Modernist chefs. Some options separate mechanically; others rely on gravitational, centrifugal, chemical, or other phenomena.

For example, a **centrifuge**, although costly, can spin foodstuffs at tens of thousands of revolutions per minute, which can lead to unexpected culinary possibilities. Using such a machine can allow you, for instance, to easily separate the pulp from any puree to create a clear, flavorful consommé in mere minutes.

A centrifuge can spin fat out of all kinds of foods. Fats extracted from vegetables and nuts can be made into constructed creams that have a consistency similar to that of dairy cream but with dramatically different flavors. Once you have used a centrifuge in your kitchen, it's hard to imagine going without one.

But not every cook has the room or the budget for a centrifuge. More conventional separation techniques can be faster and easier to use. So we begin by looking at the simplest and most widely used filtering technique: the basic sieve.

Straining and Sieving

Any home kitchen has a colander and a wire-mesh strainer. These common implements are handy for separating large, solid pieces of food from a pot of water or a newly prepared stock. But they represent the coarser end of a range of separation methods. At the other extreme are tools for extracting "fines," which are considerably smaller particles.

One step down the separation spectrum from the standard strainer sits the cone-shaped chinois, whose supposed resemblance to a Chinese peasant's hat earned it that name. The mesh of the chinois is finer than that of a household strainer. Cooks seeking even smoother, clearer liquids can line the conical bed of the chinois with cheesecloth or muslin sheets, which catch even tinier particles in their cotton-fiber meshes.

Even better are laboratory sieves, which specialists in the mineral, chemical, and other industries use to segregate minute particles by size. The finest laboratory sieves feature mesh apertures that range down to about 20 microns—that is less than a thousandth of an inch and about one-third the diameter of a human hair!

These sieves are relatively inexpensive tools that can yield purees with a rich, velvety texture or that can be used to strain a soup and give it a silky smooth texture. Some cooks deploy laboratory

Sieves are the most common separation tools in any kitchen. At the extreme, sieving becomes filtration, an essential technique of refinement.

STRATEGIES FOR FILTERING LIQUIDS AND CLARIFYING CONSOMMÉS

Filtering a liquid can remove murkiness caused by droplets of fat, bits of sediment, or other kinds of particles. The process can be as simple as pouring a stock or fruit juice through a laboratory sieve or stirring in a fining agent such as bentonite or methylcellulose. Agar and freeze clarification work by trapping fines and crystals in a web of gel, allowing only clear liquid to escape. The centrifuge is often the most efficient clarification tool because it rapidly separates solids, liquids, and oils all at once.

Select a strategy that best matches the heat tolerance and the degree of clarification, desired yield, and convenience you need.

					Applications				
Strategy	Heat	Clarity	Speed	Yield	Fruit and vegetable juice or broth	Meat or seafood broth	High-fat liquid	Puree	See page
agar filtration	cold	very good	fast	moderate	√	√			351
centrifuge	n/a	good to excellent	fast	high	√	√	√	√	360
enzyme clarification	cold to warm	good	slow	high	√				
fine lab sieve	n/a	adequate to poor	very fast	high	√	√		√	351
bentonite or polyclar fining	varies	varies widely	slow	high	√	√	√		
protein or methylcellulose fining	hot	good to excellent	moderate	moderate	√	√	√		359
gelatin ice filtration	cold	good to excellent	very slow	low	√	√	√		370
vacuum filtration	n/a	good to excellent	varies widely	varies widely	√	sometimes	√	√	356
pressure filtration	n/a	good to excellent	varies widely	varies widely	√	sometimes	√		358

Unfiltered meat stock

Büchner funnel with coffee filter

Centrifuge at 27,500*g*

Methocel raft

Agar filtration

Gelatin ice filtration

Kitchens everywhere have colanders and basic sieves. But laboratory sieves come in a much broader array of aperture sizes, ranging from 20 microns to several centimeters. We recommend having a 70 micron sieve, a 120 micron sieve, and a 250 micron sieve for versatility.

sieves to improve their control over the strength of the spices they add to dishes. Grinding peppercorns, for example, produces particles in a wide range of sizes, which, in turn, impart varying degrees of spiciness to food. Smaller pieces pack more punch than larger ones, and the tiniest bits can cause overspicing if they are not meted out judiciously. Sieving out the finer powder leaves behind a coarser collection of pepper fragments that yields a milder, crunchy seasoning on, say, a steak.

Cooks can also use sieves to manage the properties of breaded and fried dishes more precisely. The size of the breading particles on a cutlet determines how well the particles adhere to the meat and how much oil they soak up. These properties help govern just how crispy and crunchy the resulting cutlet becomes as it cooks.

Filtering by Push and Pull

Sieving and straining rely on the relatively weak force of gravity to coax the liquid through a porous barrier. A pair of somewhat more forceful techniques, vacuum filtration and pressure filtration, comes straight out of Chemistry 101.

Tomato juice (below) or meat stock (previous page) attains a range of clarities when filtered by various means. In general, the higher the clarity, slower the filtration or the lower the yield. Each of the examples below started with 500 ml / ½ qt of source liquid.

Unfiltered tomato juice

Büchner funnel with coffee filter

Centrifuge at 27,500*g*

Methocel raft

Agar filtration

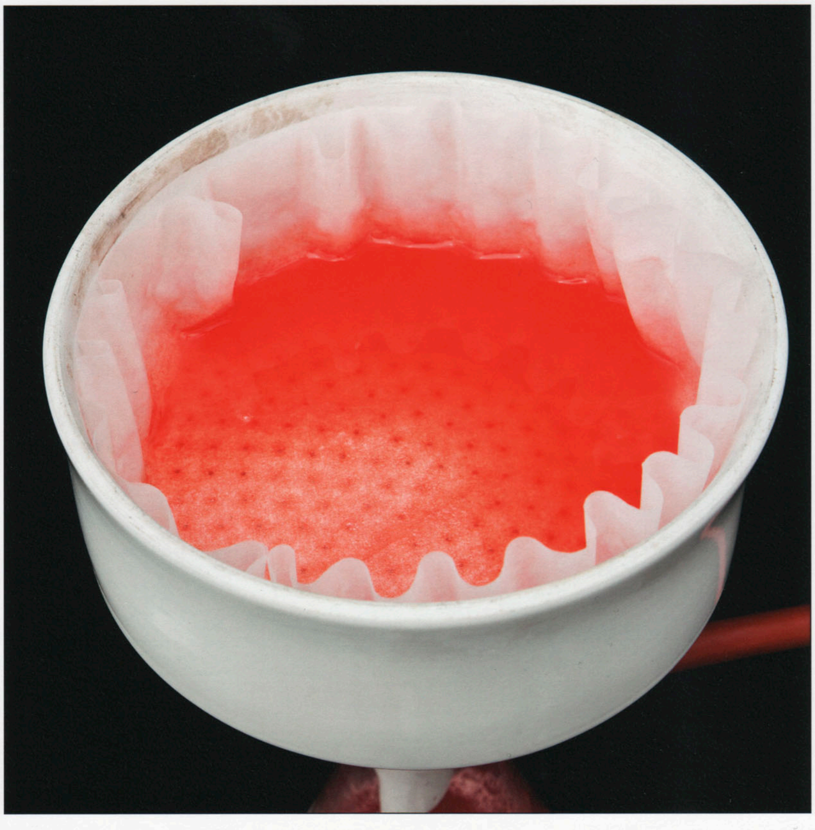
Gelatin ice filtration

At the heart of vacuum filtration is the ceramic **Büchner funnel**, an 1885 invention of the German chemist Ernst Büchner. It is a large funnel topped with a cup that has a flat, perforated bottom called the frit. The frit provides support for filter paper that sieves solids from liquids as they pass into the funnel, and go through a downspout and into a collection flask (see Filters That Suck, page 356).

The key to **vacuum filtration** is the removal of air from the flask by the suction pump (see page 356). The higher atmospheric pressure above the funnel pushes down on any liquid it contains—or, looked at another way, the vacuum below sucks the liquid through the filter.

The setup looks a bit like a chemist's version of a drip coffee maker, and it is about as simple to operate. The first step is to place filter paper in the funnel. It must completely cover the bottom plate and the holes. Wet the paper with some water, then turn on the vacuum pump. The filter paper should be sucked flat against the frit. Then pour in the liquid to be filtered, and wait for it to drip into the flask.

A standard laboratory Büchner funnel, combined with an Erlenmeyer side-arm flask and a vacuum pump, offers a simple and robust way to quickly filter many juices for sparkling clarity.



A paper coffee filter will work, but laboratory filter paper is a better choice. Standard laboratory cellulose filter papers come in many grades of fineness, in styles that are less prone to clogging, and in sizes just right for the Büchner funnel being used. A good choice of filter paper is one that retains medium to fine particles from 4–7 microns and that is still rated as having a medium to fast flow rate (such as Whatman 597 filter paper). Coarse-spun glass or quartz-fiber prefilters can be layered on top of the filter paper to catch the biggest particles.

This apparatus works well for quickly filtering plant juices to sparkling clarity, but it doesn't do a very good job on stocks and broths. Fat and oil tend to flow through the filter paper and may even be broken into finer droplets that make the stock more cloudy and turbid than before filtering! If the stock is cool enough that the fat droplets are solid particles, then filtering can remove them. Unfortunately, at temperatures cold enough to solidify the fat, the gelatin in meat juices often can become a problem. Cold stocks and broths are thick or even gelled, resistant to flowing through a filter.

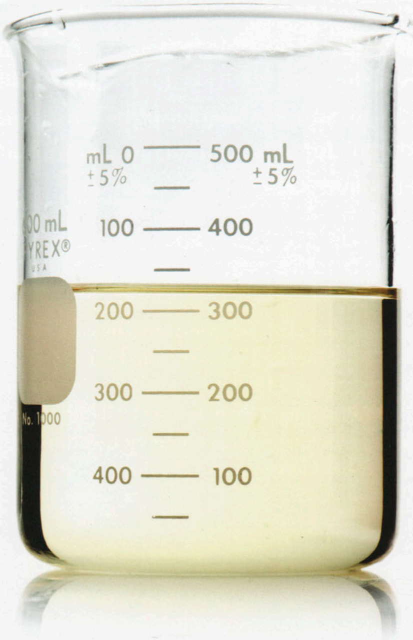
If the job is small and cost is not a huge concern, then it is possible to filter a stock or broth to prepare a consommé with the clarity of, say, Scotch whiskey in a bottle. Special membrane filter media have pores rated at 0.22 microns or finer, which is so fine that filtering the stock (while warm) will break up the oil droplets into a microemulsion that is crystal clear. A consommé prepared this way has a remarkably rich flavor (because it contains all of the flavorful oils) that is unmatched by consommés produced by other means of clarification.

Unfortunately, fine membrane filters are expensive and tend to clog quickly, and the filtered consommé will become cloudy again if you chill it because the extremely small oil droplets will aggregate into bigger fat droplets that scatter light. So this approach to filtering a broth is best done to order. For convenience, it's possible to buy self-contained disposable filter cups that have suitably fine membranes. Each cup will typically filter a couple of portions before it fouls and must be discarded.

For any kind of filtering, filters with larger surface areas will clarify more liquid before

HOW TO Clarify Juice With A Buon Vino Pressure Filter

This pressure filtration system was developed to clarify wines. But why stop there? It also provides an efficient and compact way to filter other cloudy liquids. The Buon Vino electric pump pushes juices through side-by-side plates and then through paper filters with 1–2 micron pores. The filtered juice is then collected through a hose. The only caveat when using the system is that it does not work well with gelatinous liquids such as meat stocks, which quickly clog the filter pads.



1 **Wet and insert the filter pads.**

2 **Pump hot water through the filter.** Stop when the water coming off the pads no longer has a papery taste. Slightly acidic water works best.

3 **Filter the liquid by following the manufacturer's instructions.** If flow slows dramatically, stop, and change the filter pads. Typically, you can filter several gallons before this is necessary.

Filter pads sandwiched between metal frames and plastic plates

Filtered liquid

Collection vessel for liquid that leaks

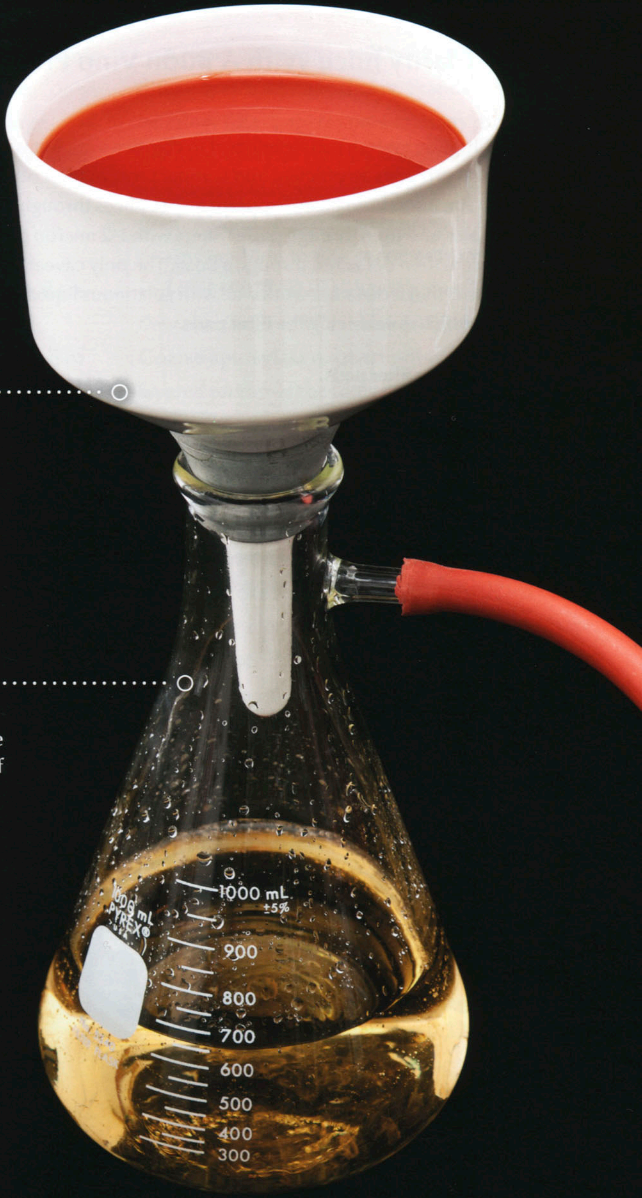
Drip tray

Electric pump

Unfiltered liquid

FILTERS THAT SUCK

When it comes to fine separation jobs, the standard combination of a sieve and gravity just isn't up to the task. Say you want to make the clearest possible fruit juice or a consommé—fast. A laboratory technique called vacuum-filtering will solve just this problem. A special apparatus supports filter paper that removes small food particles from a liquid more quickly and effectively than a simple sieve can.



A Büchner funnel is a heavy funnel usually made of porcelain, plastic, or glass. Liquids poured into the open upper chamber are drawn by vacuum through a flat, perforated disc called a frit that supports a suitable filter pad, which strains out any solid particles bigger than its pores. The filtered liquid flows down through the funnel section and through the downspout into the flask.

A sidearm Erlenmeyer flask is a thick-walled glass flask with a side outlet that connects to a vacuum pump via a heavy rubber hose. Seal the downspout of a Büchner funnel to the mouth of the flask with a rubber adapter.

A vacuum pump can be of almost any type, as long as it is designed to tolerate inflows of water vapor. Teflon diaphragm pumps used with rotary evaporators are one possibility, but they are expensive. Using oil-based vacuum pumps is not a good idea. If the pump is too powerful, you can actually suck the filter paper through the holes in the Büchner funnel.

A motorized aspirator operates like a faucet aspirator but uses an electric motor to recirculate water that is stored in a tank to generate more suction—and thus a more complete vacuum in the filter flask.

A faucet aspirator is a simple but effective suction pump that is well suited for vacuum-filtering processes. Water flowing through the aspirator tube runs past an open orifice in its side, producing a drop in pressure. The resulting partial vacuum draws air from the flask via the rubber hosing, sucking liquid down through the filter. It does create a strong vacuum, but wastes a lot of water. It is also the cheapest approach, however.

HOW TO Vacuum Filter

The particles that make liquids cloudy are thousands of times larger than the molecules that register with humans as tastes and smells. Inexpensive paper cellulose filters can pull out visible particles, clarifying liquids without greatly affecting their flavors and aromas. Often, the flavor even becomes more intense. Gravity, however, isn't strong enough to do the trick alone.

A vacuum boosts the force of gravity by harnessing atmospheric pressure to push the liquid through the filter. Vacuum filtration works faster and yields more clarified liquid than an unassisted gravity filter.

Use a sidearm Erlenmeyer flask attached to a vacuum hose, as shown on the previous page. On top of the flask, place a Büchner funnel through a single-hole rubber stopper, and place the stopper in the flask to form an airtight seal. Paper filters work best for plant-based liquids, but much finer membrane filters do the best job of clarifying meat juices. Disposable portafilters, as shown below, are available with extremely fine membrane filters, which can be used to easily vacuum filter stocks and broths. Unfortunately, they tend to clog quickly, yielding only a couple of portions before the filter is spent.

1. **Sieve the liquid through a lab sieve or a kitchen chinois (not shown).** Large particles can clog the vacuum filter and slow the process.

2. **Insert the filter paper.** Turn on the vacuum pump, and moisten the filter with a little water. Lay the paper in place, making sure it covers the holes in the funnel. Filter paper rated to retain particles between 4–7 microns works best to yield a very clear juice.

3. **Add a spun-glass-prefilter (optional).** When working with especially cloudy liquids, a prefilter traps larger particles to avoid clogging the fine filter paper beneath.

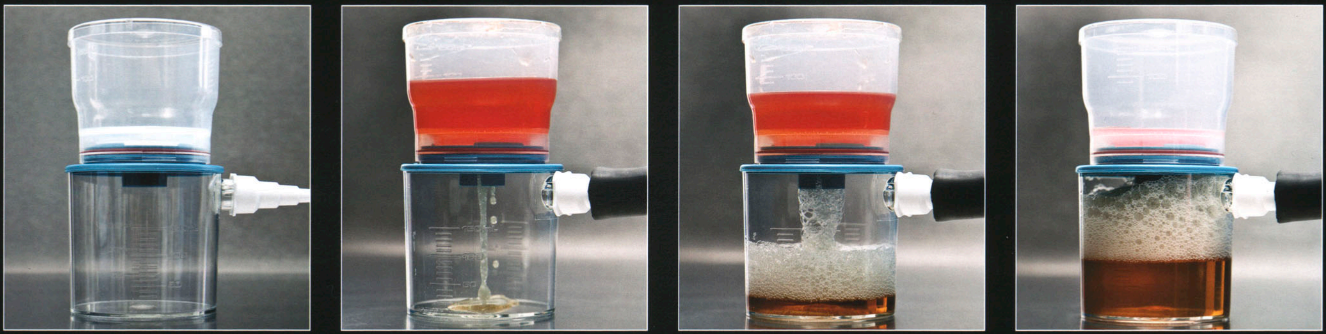
4. **Pour the fluid into the filter.** Make sure that no liquid or particles escape under the edges of the filter paper.

5. **Continue until no more juice passes through the filter.**

6. **Release the vacuum, remove the funnel, and drain the juice from the flask.**

The filtration media (such as filter paper) is the single biggest factor that determines the clarity that can be achieved. Transparency must be balanced against speed, resistance to fouling, and yield, however.

NANOSCALE PORTAFILTERS



A **portafilter** is a premade laboratory filter cup that contains an extremely fine membrane filter (220 nanometers or finer) and is disposable. It works in the same way as a Büchner funnel setup. You connect the apparatus to a vacuum pump with a rubber hose. The membrane filter clogs quickly and is overkill for most plant-based liquids, but it does a superior job with stocks and broths (although it produces low yields).

Vacuum filtration is an excellent way to remove sediment from older red wines.

fouling. Bigger funnels have more surface area and will filter more liquid faster. Ultimately, however, vacuum filtration systems can muster only so much suck. The vacuum strength can never exceed atmospheric pressure (1 bar / 15 psi) and in practice won't even reach that level.

To filter larger quantities at a faster rate, you need a more elaborate piece of equipment, one that uses positive pressure rather than a simple vacuum. A **pressure filter** encloses the filter in between sturdy metal plates. Liquid flows through channels in the frames to and from the filter pads. An electric pump then boosts the pressure above the filter to 7 bar / 100 psi. Specialized pumps used in industry filter at pressures many times higher than that.

One of the more practical pressure-filtration systems for the contemporary kitchen, the Buon Vino Jet brand of filter, is well known to home vintners. In such units, a pump forces liquid through a tight, multistage assembly of alternating frames and cellulose filter pads. Although the pump produces only around 2 bar / 30 psi of pressure, the rigorous filtration process yields extremely clear fluids. For clarifying plant juices, we find the Buon Vino Super Jet models both simple and effective.

Fining

The word "fining" suggests a kind of precise elegance. Unlike sieving and filtration, which separate solids from liquids by strictly physical means, fining exploits any one of a range of chemical techniques to improve the clarity or adjust the flavor or aroma of broths, wines, juices, and other liquids.

Fining agents work by modifying small-molecule compounds, usually organic chemicals, in ways that make them easier to sieve, filter, centrifuge, or simply settle out of the liquid. These specialized additives range from proteins such as gelatin and albumin (egg white) to bentonite (a clay-like mineral of volcanic origin) to more exotic agents like silicon dioxide powder and synthetic polymers. Even specialized enzymes are used as fining agents.

Many fining agents work by electrostatic

Fining is a versatile technique for clarifying liquids. Fining agents range from the common (egg whites) to the exotic (silica), but all work to improve clarity while minimizing the loss of flavor.

THE FINE ART OF

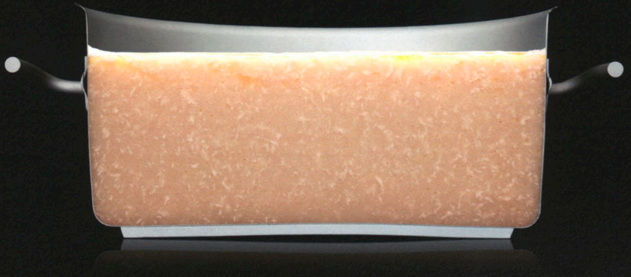
A Crystal-Clear Consommé

Lightly emulsified oil droplets are the main culprits in cloudy meat stocks. Traditionally, we strip out the droplets by forming a raft of egg whites, which destabilizes the droplets and helps them to coalesce. This improves the stock's appearance but removes some of its flavor. Many meat flavors are in the fat, so there is no way to remove the oil and retain those flavors.

There are ways to preserve many of the water-soluble flavor compounds that egg whites tend to strip out, however. The brewing and wine industries, which care dearly about aroma, have developed two good methods of clarifying. One option is to use methylcellulose. Like egg whites, this cellulose gum does a good job of sweeping fat out of emulsions and suspensions, but methylcellulose strips out fewer water-soluble aromatics than egg whites do. You use methylcellulose (below) much as you use egg whites. First, you whip the gum into a nice foam. Then you whisk the foam through a stock and apply heat. As the mixture warms, the foam binds the fat droplets together, coagulates, and rises to the surface. You can then push it aside and ladel out the clear consommé.

A second option is more counterintuitive: using meat itself as a fining agent. Meat has proteins that, like egg whites and cellulose gums, coagulate with heat. Meat is hard to whip. But you can puree it, then whisk the puree into a stock. The proteins quickly settle out of solution, clarifying the stock as they fall.

For a recipe using the steps shown below, see page 376.



attraction. The fining agents carry a positive or negative charge that attracts the opposite charge on the target particles. Examples of this type include proteins such as casein and albumin, as well as minerals such as bentonite and a silica gel (sometimes known by the trade name kieselsol).

Other fining agents include charcoal and synthetic polymers such as polyvinylpolypyrrolidone, or PVPP (brand named Polyclar). These agents are electrically neutral and work by sticking to unwanted components of mixtures, most notably phenolic compounds and other chemicals that create astringent flavors or that discolor wine and juice products. They are popular with brewers and vintners because they tend not to strip flavorful aromatics from the liquid being fined.

Most fining agents must be filtered out after they've done their job. But egg whites are a handy exception to that rule If you whip egg whites into a stock, then simmer the mix until the whites form a foamy, coagulated raft on top, the albumin proteins in the egg whites entrap both food particles and globules of fat that cloud the liquid. Ladle the floating raft out, or just poke a siphon tube through it to retrieve the clear fluid below.

Note that fining always strips out desirable aromas to the same degree it removes particles. In the case of a traditional consommé, fining removes the flavorful fat to achieve clarity, which is why it has a weaker flavor than the stock from which it was prepared.

Plant-derived methylcellulose powder works much like egg whites, but it diminishes less of the water-soluble, meaty flavor of a stock. Polyclar also avoids stripping out aromatics, but the polymer has its own drawbacks: it is less effective at removing large quantities of emulsified oils, and its very fine particles tend to remain suspended in the liquid, so you must filter out the Polyclar after it has done its job.

Pureed raw meat offers still another alternative as a fining agent. Whisked into a stock or broth and then heated, the protein in the meat first coagulates in the liquid, then settles to the bottom, sopping up solid particles and fat as it sinks. This is a trick that Chinese cooks having been using to clarify broths for centuries.

Putting a Spin on It

Most people have a centrifuge—a machine for spinning things fast—in their homes. It usually sits in the basement and goes by the name of "washing machine." Its spin cycle forces water from the clothes by spinning the drum. A salad spinner dries lettuce in much the same way.

The same principle can be used in the kitchen to separate things by density. The laboratory centrifuge is an exciting new tool for chefs, although it has been used in science labs for more than a century. Often the size of a dishwasher, this machine imposes gravity-like forces on the cup-size vials of liquid it spins around—but it exerts forces tens of thousands of times stronger than Earth's gravity.

A centrifuge opens the door to a universe of unusual concoctions. And each new centrifuge-born creation can, in turn, serve as the base for myriad other preparations in the kitchen.

The centrifuge gets its name from the centrifugal force it generates when it spins a liquid mixture at high speed. A centrifugal force is the same sort of sideways push you feel while driving a car around a sharp turn at high speed or when sitting in a fast-spinning carnival ride.

The most powerful centrifuges can whirl a vial of fluid around 60,000 times a minute (rpm), creating up to 250,000 times that of Earth's gravity, which is 1*g*. Just as normal gravity causes a rock to sink in water and less dense wood to float, this artificial form of gravity forces denser components of a mixture, like particles of solids, to sink to the bottom of the vial (toward the periphery). Meanwhile, lighter components, like oils and fats, float to the top (near the central axis). Watery solutions settle somewhere in between. Gravity could achieve similar separation, but inside the centrifuge, the process happens tremendously fast.

If you spin just-prepared carrot juice in a centrifuge, the sharp-tasting pulp will travel to the bottom of the bottle and form a puck of sediment. You may even notice that the solid matter contains a whitish fraction of bitter-tasting minerals. Above the puck, however, will be a very sweet juice unlike any carrot juice you have ever tasted.

Despite its brawny character, a centrifuge cannot defeat the physical chemistry that keeps some common emulsions well mixed. In homogenized cream, for example, casein proteins lock

Centrifuges use rotational forces to separate food into layers by density. Eight different layers are clearly visible above in the centrifuged stewing juices captured from our recipe for Hungarian Beef Goulash (see page 5·55).

THE IMPORTANCE OF

Centrifuge Safety

Laboratories have been destroyed by centrifuge accidents. The smallest crack in a rotor can lead to catastrophic failure, and the near-instantaneous release of all that rotational energy is like the explosion of a small bomb. You definitely do not want to be nearby if it happens.

Modern centrifuges are designed to detect problems and shut down if necessary, but these safety features are not foolproof. You must treat your centrifuge rotor carefully; never drop or otherwise abuse it. You must also have specialists test your rotor periodically, depending on how often you use it and at what speeds. Any major city will have a centrifuge-repair specialist who services the units in local medical laboratories.

Technicians may use x-ray imaging or apply a penetrating dye to search for tiny or invisible cracks. When you buy a centrifuge, it is very important to get your machine and rotor verified by a certified technician, especially if you purchased it secondhand.

YOU SPIN ME RIGHT 'ROUND

What happens when you subject food to accelerations that are up to 30,000 times as strong as Earth's gravity? A centrifuge lets cooks explore the possibilities. This sophisticated device, commonly found in chemical, medical, and pharmaceutical laboratories, can separate out the minute quantity of fat in a tomato puree, quickly split a fruit juice from its pulp, and concentrate the flavor of an herb puree. A centrifuge can easily do what no other machine can.

A centrifuge spins liquids at very high speeds, causing particles suspended in a liquid to segregate by density, exactly the way that gravity causes fat to rise to the top of a stock and bones to fall to the bottom. But rotation at tens of thousands of revolutions per minute generates huge forces that speed the normal separation process enormously.

Well-heeled cooks can choose from among several kinds of centrifuges. Restaurant chefs would be well served by units that are about the size of a washing machine and can process up to 3 l / 3 qt of food at a time, at rotational speeds up to about 30,000 rpm.

Blood-bank centrifuges, used to separate red blood cells from plasma, can handle larger quantities of liquid, but they typically generate weaker forces. Desktop centrifuges can accommodate only much smaller fluid samples, so they are often not very useful in the kitchen.

Ultracentrifuges are lab-grade machines that can generate forces approaching a million times that of Earth's gravity. Ultracentrifuges can yield amazing culinary results, albeit only in maddeningly limited quantities.

The rotor holds the flasks of liquid to be spun. A motor spins it up to tens of thousands of times a minute. This precision component undergoes enormous stresses, so it must be both extremely light and strong. Rotors are made out of high-strength aluminum, titanium, or carbon-fiber composites.

The even number of holes in the rotor allows the operator to balance the weight symmetrically about its central axis. An unbalanced centrifuge rotor is unacceptable; it will vibrate dangerously and can cause the machine to break.

Flask caps should be closed tightly.

Many high-quality centrifuges are refrigerated to counteract the heat that air friction creates on the outside of the spinning rotor. Unless this heat buildup is controlled, it can damage or cook the liquid being spun. A top-of-the-line model allows you to control the temperature from about 40 °C / 104 °F to about −20 °C / −4 °F. That capability can be useful for removing fat from a stock, for example. You can initially separate the stock at a higher temperature, then cool that stock down to solidify the fat on top. This technique makes it easy to drain off the clarified liquid.

HOW TO Balance a Centrifuge

It is critical to safe centrifuge operation that each pair of samples set on opposite sides of the rotor weigh the same amount. Each rotor and each centrifuge has a particular tolerance for unbalanced samples. Be aware of what that tolerance is.

1 **Divide the total weight of the liquid by the number of bottles to be used.** For example, if you will be spinning 1,800 g of liquid in six bottles, each bottle will hold no more than 300 g. Set the target weight by deducting a few grams to account for loss during pouring.

2 **Place an empty bottle and a lid on a scale, and tare to zero.**

3 **With the lid still on the scale, fill the bottle with liquid until the target weight is reached.** Top with the lid, and tighten.

4 **Place another empty bottle and lid on the scale, but do not reset the tare weight.** Bottles and lids often vary in weight. For bottles after the first, always use the original tare or zero setting, even if it reads a few grams heavier or lighter. Fill to the same final weight as the first bottle.

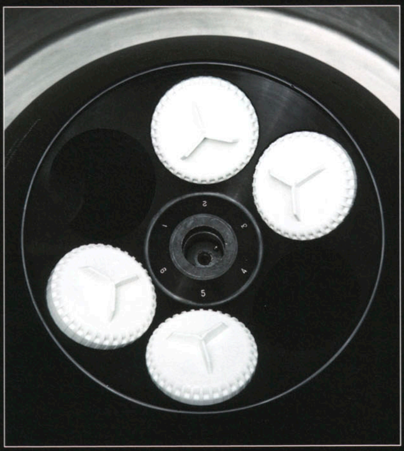
5 **Repeat steps 3 and 4 until all bottles are filled.** If you do not have enough liquid to fill all bottles evenly, you can substitute bottles of water at the same weight. You can also use an eyedropper or pipette to remove or add liquid to balance the weights of the bottles.

6 **Insert the balanced bottles into the rotor of the centrifuge.** Make sure they are distributed evenly.

3

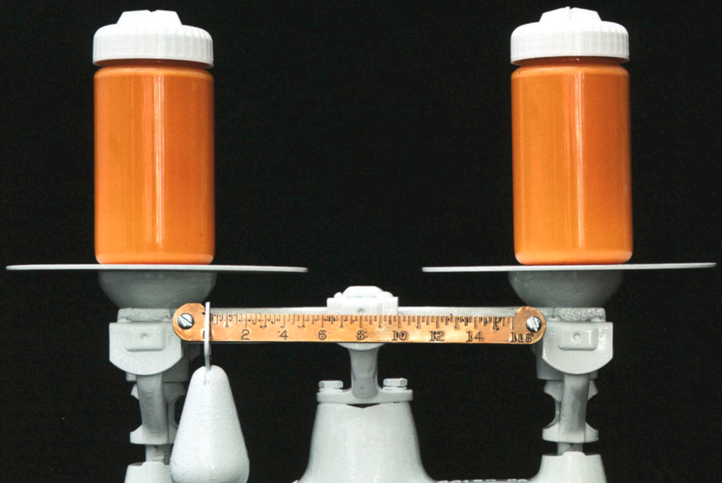
5

6



VARIATION: Pair Centrifuge Bottles with a Balance Scale

You can balance the rotor by pairing bottles and caps on a balance scale. Be sure to seat the matched pairs opposite each other in the rotor.



HOW TO Separate Liquids By Centrifuging

The centrifuge is our favorite tool for collecting flavorful fats like carotene butter, for clarifying fresh fruit waters, and for creating sparkling clear consommés. The rotor generates heat as it spins, and, although this warmth helps liquids separate a bit more quickly, it may cause unwanted changes to liquids that are sensitive to heat. Consider buying a centrifuge that has a refrigeration unit. When using a centrifuge, always follow the safety recommendations on page 361.

1 **Load bottles into the rotor.** If not filling the rotor completely, place balanced pairs of bottles opposite one another (see previous page).

2 **Select the highest rotor speed available (not shown).** The highest *g*-force generally works best unless you want a specific result, such as less separation, that only a slower spin rate will achieve. If the centrifuge has a temperature control and the liquid is heat sensitive, set to refrigerator temperature (5 °C / 40 °F).


1


3

3 **Run the centrifuge.** The time required depends on the liquid. At top speed, most liquids need 10–60 min to separate fully.

4 **Remove bottles gently.** Try not to agitate the separated liquids.

5 **Separate the layers.** For fresh cream or carotene butter, chill the bottles, poke a hole through the hardened fat, and pour off the liquids. For vegetable waters, use a pipette to gather any essential oils. After decanting the liquids, scrape out the solids.


4


5

EXAMPLE RECIPE

CENTRIFUGED CAROTENE BUTTER

As rare as they are in most kitchens, centrifuges are among the most versatile and labor-saving devices worthy of a chef's investment. Unattended, these workhorses can beautifully clarify liquids, pull emulsions apart, separate solids that would otherwise require painstaking filtering, and perform many other useful tasks. We recommend using models that are about the size of a washing machine and capable of handling 2 l / 2 qt or more at a time.

Yields 1.4 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Carrot juice see page 365	2.2 kg (from 3.5 kg of carrots)	100%	① Bring 1.4 kg of carrot juice to a simmer. ② Blend in butter, and simmer for 30 min. ③ Blend in remaining 800 g of carrot juice.
Unsalted butter, cubed	1.4 kg	64%	④ Divide mixture equally (check weight) among centrifuge bottles. ⑤ Centrifuge bottles at 27,500*g* for 1 h. ⑥ Refrigerate bottles until butterfat has solidified, about 2 h. ⑦ Pierce congealed butterfat on top of each bottle. ⑧ Pour out clarified carrot juice, and set aside for another use. ⑨ Warm bottles in water bath, or microwave to melt butter. ⑩ Decant clear, melted butter, and discard accumulated solids from bottoms of bottles. ⑪ Vacuum seal and refrigerate until use.

(2008)

HOW TO Separate Fresh Butterfat from Cream

Butterfat floats to the top of farm-fresh milk, but in commercially produced products, homogenization prevent this. Anyone who grew up near dairy cows knows the inimitable pleasure of spreading fresh, pure butterfat onto sliced bread or slurping it up with sweet, recently picked fruit. To reproduce this in the modern kitchen, you need to split butterfat from cream by following the steps below. The butterfat will be fresh and somewhat floral but not especially sweet because the lactose is discarded along with the proteins and even the locust bean gum.

1 **Blend in 1 g locust bean gum for every 100 g of cream.** Choose a high-fat cream for the best yield. Avoid creams with an added stabilizer; they will not break easily.

2 **Warm the mixture to 30–40 °C / 86–104 °F.**

3 **Centrifuge the mixture for 20 min at 27,500*g*.**

4 **Chill bottles to solidify the butterfat.**

5 **Pierce the fat and pour out the liquid.**

6 **Warm the bottles to melt the fat.** Pour it out and refrigerate until use.

If you do not have a centrifuge, you can use the slower approach of simply mixing the cream with locust bean gum then allowing it to rest in the refrigerator. After a day or so, most of the pure butterfat will rise and settle on top of a thin, yellowish liquid similar to whey.

EXAMPLE RECIPE

TOMATO WATER

Yields 1.2 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Tomatoes, peeled, seeded, and chopped	2 kg	100%	① Process with Champion-style juicer. ② Measure evenly among centrifuge bottles. ③ Centrifuge at 27,500*g* for 1 h, and decant.
Salt	to taste		④ Season juice, and refrigerate until use.

(2007)

Vacuum filters, wine filters, and enzyme clarification are good alternatives to centrifuging when making tomato water.

EXAMPLE RECIPE

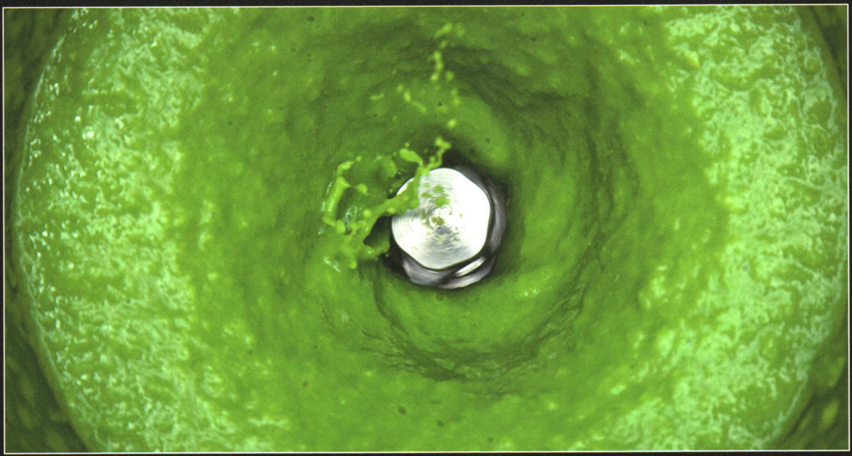
CENTRIFUGED PEA JUICE

Yields 325 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Frozen sweet peas, thawed	700 g	100%	① Blend to fine puree.
Water	70 g	10%	② Divide evenly among centrifuge bottles, ensuring filled bottles are of equal weight.
			③ Centrifuge bottles at 27,500*g* for 1 h.
			④ Decant juice, and filter, to obtain about 325 g.
			⑤ Skim off and reserve layer of surface fat, about 50 g.

(2009)

Adding 0.2% of Pectinex Smash XXL enzyme to fruit and vegetable purees and juices before centrifuging can both speed the separation process and increase the yield by up to a factor of two—see page 377.



EXAMPLE RECIPE

CENTRIFUGED ROASTED-HAZELNUT OIL

INSPIRED BY NILS NORÉN AND DAVE ARNOLD

Yields 150 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Hazelnuts	400 g	100%	① Roast in **160** °C / **325** °F oven for 25 min.
			② Transfer while warm to food processor.
			③ Blend to form smooth butter.
Sugar	40 g	10%	④ Combine, and bring to a boil to make syrup
Water	40 g	10%	⑤ Remove from heat.
			⑥ Blend syrup with hazelnut butter.
			⑦ Divide mixture evenly among centrifuge bottles.
			⑧ Centrifuge at 27,500*g* for 1 h.
			⑨ Decant oil on top, and refrigerate until use.

The sugar syrup dramatically improves the yield of the product by helping to force a cleaner separation between the layers. It also sweetens the result, however. Use plain water to boost yield without adding sweetness.

(original 2009, adapted 2010)

Centrifugation affects different mixtures in different ways. Some need an added liquid that is intermediate in density between the lightest liquids and the densest solids in the mixture. Some need more time or centrifugal acceleration. Experiment to get the best separations.

For more on how to use a centrifuge to separate cream, see page 366.

away fat globules in suspension by enveloping them in molecular blankets. Electrostatic charges on the casein molecules attract fats to the inside surface while opposite charges on the other ends of the protein molecules bond with the milk's watery matrix.

In homogenized cream, you can disrupt these suspended colloidal particles by adding some locust bean gum. A spin cycle in a centrifuge will then pull the fatty cream right out of the denser milk. Perform the cycle under refrigeration, and the cream at the top hardens, allowing you to decant the underlying liquid easily by simply poking a hole in the crust. Et voila! Concentrated, fresh cream.

And not just cream, but lactose-free cream, because the lactose sugar remains dissolved in the milk after centrifugation. Also absent from the homemade cream are water-soluble compounds such as diacetyl, which forms the foundation of butter flavor. The dairy cream that comes out of a centrifuge therefore offers cooks a unique, flavor-neutral dairy fat that has myriad uses in the kitchen.

Additives of several kinds can intensify the extent of the separation that occurs during spinning, yielding liquids that are even clearer and more colorful. These agents alter the density of the liquid mixtures that go into the centrifuge bottles. Adding glycerol to an herb puree, for instance, makes the watery fraction less dense so that it separates more readily from the solids in the mix. Adding sucrose, on the other hand, makes a watery matrix denser. A sugary additive can thus improve the separation of oils and fats from liquids, like milks, that contain water and fat.

Clarity by Ice or Gel

Centrifuges, Büchner funnels, and Buon Vino pressure filtration systems are wonderful tools, but even if you have nothing more than a freezer, a refrigerator, and a gelling agent such as gelatin or agar, you can still clarify strained stocks, sauces, purees, and almost any flavorful liquid to a gratifying extent. The secret is to exploit the concentrating effect of freezing, and the net-like molecular structure of a gel, which can behave much like a filter with truly microscopic—even nanoscale—pore sizes.

One way to make a filter from frozen gel is to add gelatin to the liquid you want to filter and to freeze the mixture. Once it is frozen, transfer the mixture into a strainer placed over a bowl, and thaw it slowly in a refrigerator for a day or two (see How to Filter with Gelatin Ice, page 370).

The temperature in the refrigerator is cold enough to keep the net of gelatin molecules intact

but warm enough that the ice crystals slowly thaw. As the freed water trickles down through the gelatin network and into the bowl (in a process scientists call **syneresis**), it washes out soluble sugars and flavor molecules that have become trapped in the gel—including food particles, fat, and other impurities that can cloud liquids. Meat stocks often contain enough gelatin naturally to gel as they cool, but cooks need to add small amounts of gelatin directly to fruit and vegetable juices to clarify them in this way.

A wonderful aspect of the freeze filtration process is the fact that the liquid that leeches out of the mix first contains a far higher concentration of soluble flavor compounds and pigments compared with that which weeps out later. If you don't mind throwing away some of the overall yield, this approach thus affords a simple way to select the intensity of a juice's flavor: just use the fraction with the strength you want.

Gel filtration has an interesting history. The German scientist Gerd Klock discovered a way to use agar, a gelling agent derived from seaweed, to filter liquids with remarkably clear results. Glock presented this approach at an INICON conference where Chefs Heston Blumenthal and Albert Adria were both in attendance. In discussions between Klock and Blumenthal, the possibility of applying the technique to gelatinous stocks was considered and later applied successfully in the kitchens of The Fat Duck. Concentrated, gelatinous broths are first frozen, then strained in the refrigerator over a period of days. The particulates are trapped in the fine mesh of protein strands.

The technique of gelatin filtration travelled across the Atlantic to wd~50 in 2005, after the New York City chef Wylie Dufresne visited Blumenthal at The Fat Duck in England, where he saw a gelatin-clarified venison stock. Dufresne realized that the same process could work for any liquid, including plant juices. All that needed to be done, he reasoned, is to add the appropriate amount of gelatin (typically 1%–2%)to any liquid that doesn't already have it naturally.

The process soon spread widely. Aki Kamozawa and Alex Talbot, the authors of the blog Ideas in Food, learned about the process while spending time in the kitchen at wd~50 and then adapted it to work with agar for vegetarian preparations, thus bringing it full circle to Glock's original approach. They reasoned that mechanically breaking up the gel would increase syneresis and accelerate the filtering process by eliminating the slow freeze–thaw step. Influenced by Ideas in Food, David Arnold and Nils Norén of the French Culinary Institute in New York City refined the idea to boost its speed and yield. Both techniques are now used widely in Modernist kitchens worldwide.

Syneresis refers to the tendency of gels to weep liquid (see page 372). It is usually a problem in the kitchen, but the gel filtration technique exploits it.

HOW TO Filter with Gelatin Ice

Freeze filtering is a technique that uses syneresis, the tendency of a gel to degrade and leak liquid, as a feature. The network of molecules in the gelatin that creates the gel form a filter that traps particles. This approach can be used both to clarify and to intensify or concentrate.

1 **Weigh a juice, rest, and pour approximately one-quarter of it into a pot.** Reserve the remainder for later use.

2 **Weigh a quantity of 160 Bloom gelatin equal to 1% of the total juice weight, and hydrate it fully (not shown).**

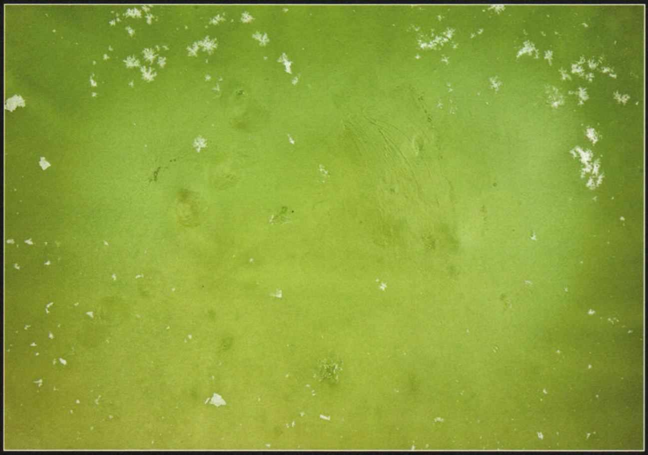
3 **Add the hydrated gelatin into the juice in the pot.** Whisk over low heat until the gelatin is completely dissolved.

4 **Mix in the reserved fresh juice.**

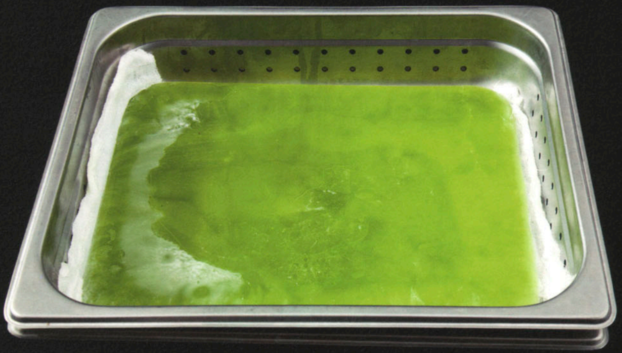
5 **Pour into a hotel pan to form a layer no more than 5 cm / 2 in thick.**

6 **Freeze the mixture.**

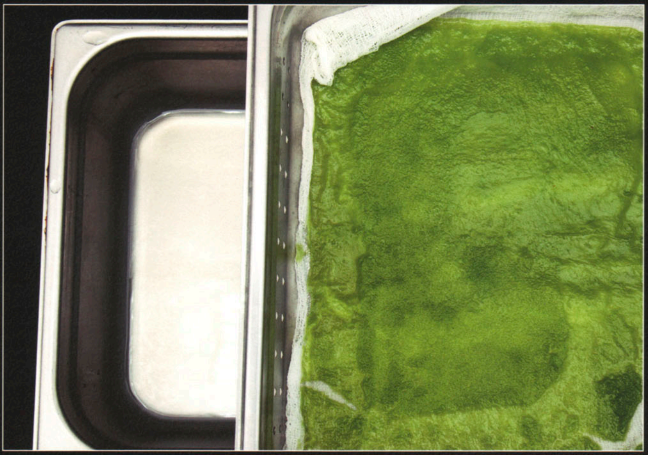
For stocks that naturally contain gelatin, the first five steps can be skipped.



7 **Dip it (not shown).** Dip the hotel pan briefly in warm water to free the block of frozen juice.



8 **Assemble a strainer.** Place the frozen juice on muslin in a perforated hotel pan, then set that pan on a nonperforated hotel pan to capture the melting liquid.



9 **Refrigerate the setup for 24–48 h as the juice thaws (not shown).**

10 **Decant the clarified juice from the bottom tray.** Discard the remaining frozen juice.

For stocks and other liquids that contain fats and oils, it's best to thaw the frozen block at refrigerator temperatures. Warmer temperatures cause some fats to thaw and wash out in droplets that cloud the liquid. For fat-free juices, however, thawing at a cool room temperature can speed the process without compromising the clarity of the filtered juice.

HOW TO Clarify Liquids with Agar

Freeze filtering, for all its benefits, also has limits: it takes time and advance planning, it isn't ideal for fragile liquids that taste best when ultrafresh, and it consumes valuable refrigerator and freezer space. When these factors are an issue, we turn instead to agar gels.

Aki Kamozawa and H. Alexander Talbot, authors of the blog Ideas in Food, found that agar makes a good substitute for freeze filtering, because it eliminates the time-consuming step of freezing. Instead, they used agar to make the liquid to be filtered into a thin gel that is highly prone to syneresis (weeping).

David Arnold and Nils Norén further simplified the technique. For more heat-sensitive juices, such as lime juice, hydrate the agar in water and add juice at room temperature to the boiling agar-water mix once you have removed it from the heat. Use one part water to four parts juice.

Agar syneresis can also be used as a strategy for concentration. To do this, follow steps 1–9 below and retain just the first press extracted from the gel, which contains the most intense flavors. Each subsequent press produces more dilute liquid.

1 **Weigh 500 g of cold orange juice, 250 g of cold orange juice, and 1.5 g of agar (not shown).**

2 **Whisk the agar into the 250 g of cold juice until it is fully dispersed.**

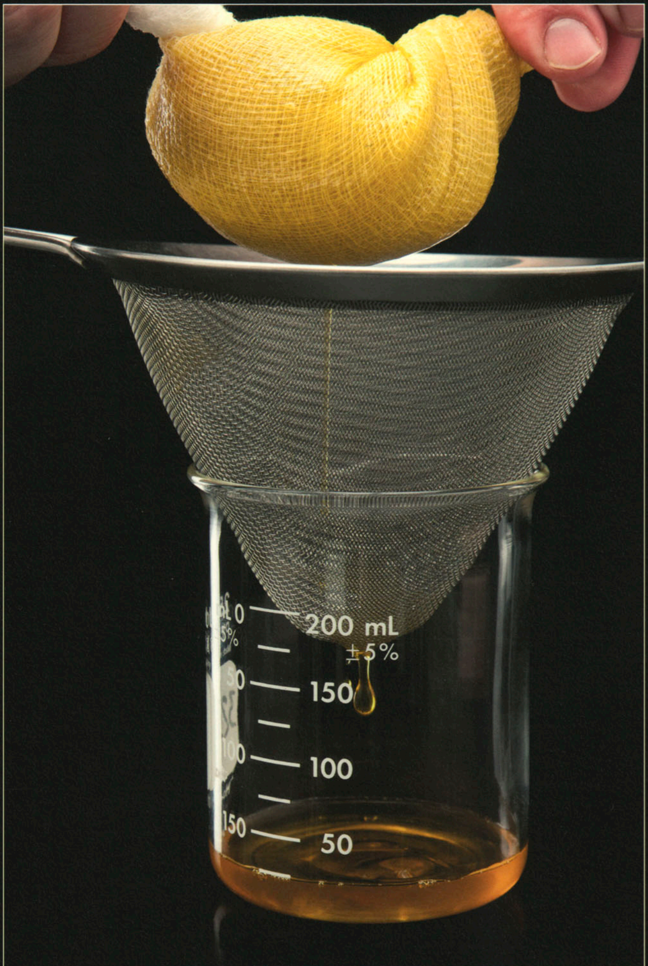
3 **Heat the mixture to a boil while whisking.** Simmer it for a few minutes to hydrate the agar. Or hydrate agar in water separately, then add juice.

4 **Add the 500 g of cold juice in a thin stream while briskly whisking the boiling solution (not shown).** Don't let the temperature drop below 35 °C / 95 °F.

5 **Sieve the solution.**

6 **Place the sieved solution on an ice bath to set (not shown).**

7 **Break up the set agar into curds with a whisk.** Be gentle.



8 **Place the curds in a cheesecloth-lined chinois over a container.**

9 **Lift the cheesecloth and gently squeeze it to drain.** Don't twist hard, or the agar will extrude out of the cheesecloth.

10 **Return the curds to a bowl and repeat steps 7–9 for additional yield (optional).**

PARAMETRIC RECIPE

CONSOMMÉ

A consommé is a thin, crystal clear soup, sometimes embellished with a classic garnish. There is nothing relaxed or casual about a consommé. It is meant to demonstrate a chef's skill and expertise. In classical cuisine, chefs enhance a basic broth by adding poultry, fish bones, or sinewy cuts of meat to contribute gelatin and improve viscosity. They then meticulously clarify the broth by whisking it with hot, foamed egg whites, and leave it to drip through fine linen. The starting soup must harbor very strong flavors to withstand such extraction; even so, a good splash of sherry is commonly added just before service to enliven the taste.

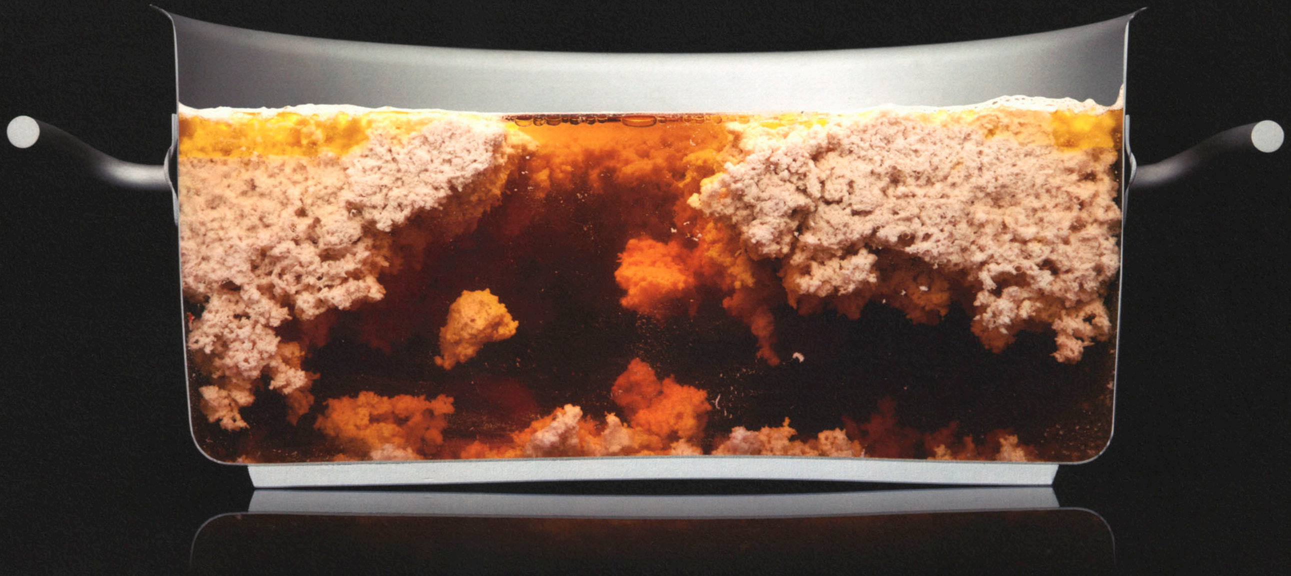
Advanced tools, such as filters and centrifuges, as well as clever techniques such as frozen filtration, enable cooks to eliminate the flavor-stripping and somewhat tedious raft of egg white.

CLARIFYING A CONSOMMÉ

1. **Select a recipe.** See the table below for suggestions.
2. **Combine the liquids, flavoring agents, and aromatics.** Quantities given in the table are proportional to the weight of the principal liquid. For example, use 8 g of lager for every 100 g of stock when making bacon consommé.
3. **Cook (if applicable).** Recommended cooking methods, temperatures, and times are indicated in the table. If cooking sous vide, vacuum seal all ingredients together.
4. **Clarify.** See Strategies for Filtering Liquids and Clarifying Consommés on page 352 for more details on the clarification methods suggested in the table; alternative strategies may work as well.
5. **Season.** For seasoning options, see Best Bets for Lowering pH on page 314, Seasoning with Salt and Other Flavor Enhancers on page 312, and Best Bets for Adding Flavor with Alcohol on page 317.

Best Bets for Consommé

Recipe	Liquid	(scaling)	Flavoring	(scaling)	Aromatics	(scaling)
bacon consommé	white pork stock lager	100% 8%	bacon, thinly sliced	50%	sweet onions, thinly sliced black pepper maple syrup	25.0% 3.5% 5.0%
brown butter consommé	white chicken stock butternut squash juice vodka	100% 20% 5%	brown butter extract see page 331	5%	star anise saffron	0.3% 0.1%
chocolate water adapted from Sam Mason	water	100%	dark chocolate (80% cocoa)	24%	cocoa nib cocoa powder	10.5% 10.0%
consommé madrilène	white chicken stock tomato water see page 366 vermouth	100% 100% 5%	ground chicken, browned tomato, peeled and seeded	30% 15%	coriander seed star anise	0.5% 0.1%
kimchi consommé	ramen stock	100%	kimchi, pureed	6%	fish sauce lime juice	to taste to taste
Parmesan water	water	100%	Parmesan cheese, grated	100%		
pea consommé	pea juice	100%	cinnamon essential oil (optional)	to taste	lime juice	0.01%
rhubarb water	rhubarb juice	100%	white soy sauce	12%	lime juice fructose	2.5% to taste
shellfish consommé	shellfish stock	100%	lobster bodies crab knuckles shrimp shells	30% 20% 12%	onion, thinly sliced carrot, thinly sliced tomato paste	4% 4% 1%



	Cook			
Method	(°C)	(°F)	(h)	Clarify
cook sous vide	88	190	2	freeze filtration
cook sous vide	80	176	1	vacuum filtration
cook on stove top	90	194	10 min	centrifugation
cook sous vide	80	176	1	methylcellulose fining
infuse sous vide	refrigerated		24	agar filtration
cook sous vide	88	190	1½	freeze filtration
	n/a			centrifugation
	n/a			Buon Vino wine filter or Büchner funnel with Whatman 597 paper
fry shells, cool, cook sous vide	88	190	1	centrifuge

EXAMPLE RECIPE

OXTAIL CONSOMMÉ INSPIRED BY DAVID BOULEY

Yields 2.5 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Spanish onions, peeled and halved	500 g (two large onions)	25%	① Sear cut side down until light golden, about 8 min. ② Cool.
Water	50 g	2.5%	③ Vacuum seal with seared onions. ④ Cook sous vide in **85** °C / **185** °F bath for 7 h. ⑤ Transfer mixture from bag to bowl, and cool. ⑥ Strain, discarding onion solids. ⑦ Measure 250 g of onion jus, and reserve.
Oxtail, jointed	1.5 kg	75%	⑧ Brown oxtail over high heat on all sides until golden, about 15 min.
Neutral oil	30 g	1.5%	
Brown beef stock see page 301	2 kg	100%	⑨ Combine with browned oxtail in pressure cooker. ⑩ Pressure-cook at a gauge pressure of 1 bar / 15 psi for 2 h. ⑪ Strain, discarding solids. ⑫ Measure 2 kg of oxtail broth.
Onion jus, from above	250 g	12.5%	
Gin	250 g	12.5%	
Veal marrow	250 g	12.5%	
Button mushrooms, thinly sliced	150 g	7.5%	
Carrots, peeled and thinly sliced	100 g	5%	
Celery stalk, peeled and thinly sliced	30 g	1.5%	
Oxtail broth, from above	2 kg	100%	⑬ Mix 200 g of broth with super methylcellulose. ⑭ Whisk into ground beef to make paste. ⑮ Mix paste into remaining oxtail broth for consommé. ⑯ Simmer consommé on low until clarified, about 45 min. ⑰ Strain.
Ground beef	300 g	15%	
Super methylcellulose SGA 150 (Dow brand)	2 g	0.1%	
Bay leaf extract see page 326	to taste		⑱ Season.
Lovage leaves, fine julienne	to taste		
Salt	to taste		
Star anise extract see page 326	to taste		

(2010)

For photos of the steps involving methylcellulose, see page 359.

EXAMPLE RECIPE

PISTACHIO CONSOMMÉ

Yields 80 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Raw pistachios, shelled	100 g	100%	① Combine. ② Roast in **190** °C / **375** °F oven until very dark and sugar has caramelized, about 20 min.
Sugar	15 g	15%	
Grapeseed oil	10 g	10%	
Water	300 g	100%	③ Puree with roasted pistachios until smooth. ④ Vacuum seal. ⑤ Refrigerate for 12 h. ⑥ Centrifuge at 27,500*g* for 1 h. ⑦ Decant clear liquid through fine sieve, and discard remaining solids.
Pistachio oil	20 g	20%	
Salt	to taste		⑧ Season. ⑨ Vacuum seal, and refrigerate until needed.

(2009)

The remaining nut solids in the centrifuge bottles are not used for anything in this recipe or these volumes, but they're a delicious snack for the chef.

EXAMPLE RECIPE

APPLE CIDER CONSOMMÉ

Yields 850 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Sugar	40 g	8%	① Cook over high heat; allow caramel to become dark.
Water	20 g	4%	
White miso paste	10 g	2%	
Water	40 g	8%	② Deglaze caramel. ③ Whisk until dissolved. ④ Cool.
Apple cider	500 g	100%	⑤ Combine with caramel water.
Green apple juice	250 g	50%	⑥ Vacuum seal.
Cider vinegar	10 g	2%	⑦ Refrigerate for 4 h to infuse.
Malic acid	6 g	1.2%	⑧ Strain.
Salt	6 g	1.2%	
Thyme leaves	6 g	1.2%	
Pectinex Smash XXL (Novozymes)	1.6 g	0.32% *(0.2%)**	⑨ Whisk into juice. ⑩ Pour into tall, clear container, and refrigerate for 24 h to clarify. ⑪ Decant clarified liquid without disturbing the solids settled at the bottom. ⑫ Check seasoning. ⑬ Serve with grilled mackerel or raw foie gras dressed in walnut oil.

(2010)

**(% of total combined weight of apple cider, green apple juice, and cider vinegar)*

During the clarification process, the enzyme will force solids to the bottom of the container. See page 352 for more clarification methods.

A rotary evaporator is one of the more exotic and powerful tools for concentrating flavor.

CONCENTRATE!

Skilled cooks strive to intensify the flavors in their dishes by concentrating the essences of certain ingredients as much as possible without significantly altering them. Concentrating is usually about removing excess solvent from a food. The most common solvent in the kitchen is water (but occasionally alcohol); removing it makes tastes and aromas stronger. There are other times when, rather than discarding it, collecting the solvent and any flavors it contains is the goal.

Chefs traditionally strengthen the flavor of a stock, juice, or sauce by subjecting it to a long simmer to reduce its volume. This process is concentration by evaporation. It works because we can evaporate water by using heat. This trusted technique does a great job of concentrating nonvolatile flavor components of the original solution such as sugars, salts, and flavor-enhancing molecules like savory-tasting glutamates and nucleotides.

The classic reduction method also tends to thicken the liquid by increasing the concentration of gelatin, emulsified oils, and any dissolved or suspended solids such as sugars or particles in a puree. Reducing a liquid thus usually changes its mouthfeel as well as its flavor.

Unfortunately, these changes are not always for the better. The same heat that boils the water also breaks down or alters some of the most desirable aroma compounds in the mix. Even worse, higher

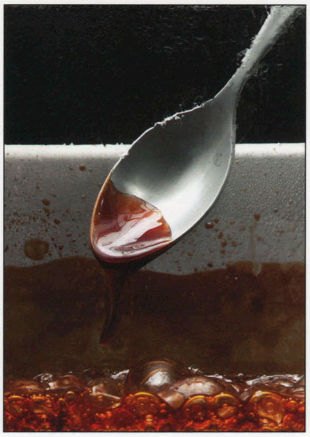
STRATEGIES FOR CONCENTRATING

A cook has many options for intensifying the flavor of liquids that come from food. The alternatives range from the traditional boiling pot on the stove to the more exotic and expensive, such as Genevac's Rocket Evaporator, which is part centrifuge and part distillery. You can use any of these strategies to concentrate a juice, jus, or broth.

Strategy	Description	Pros	Cons
stove-top reduction	boils off water to increase concentration of those flavor compounds that remain	inexpensive, easy	slow, many desirable volatile aromatics evaporate away or are altered by heat
vacuum reduction	lowers pressure of air above liquid, increasing rate of evaporation	inexpensive, straightforward to set up	volatile compounds still escape
rotary evaporation (rotavap)	distills and captures volatile components selectively at a controlled temperature and pressure	captures evaporated volatile aromatics, reduces without heat, processes large batches	expensive, complicated
vacuum concentration (with vacuum concentrator)	spins liquids at low speed, distills under vacuum, and condenses evaporated components	simple automated process handles up to six liquids at once, precise temperature control, low-speed centrifugation	expensive, complicated
freeze concentrating	forms crystals of pure ice that force particles and dissolved substances to concentrate in remaining liquid	very inexpensive and simple, requires no special equipment, no volatiles escape or change	slow, limited degree of concentration
reverse osmosis	forces liquid through a semipermeable membrane through which water, but not flavor compounds, can pass	energy-efficient, commonly used in water purification and wine making	complicated, not yet adapted for culinary use

temperatures evaporate many of the prized volatile aromatic compounds in the solution. Food fragrances filling your kitchen may smell great, but they are signs of a deficiency in the reduction process: if you can smell the aroma compounds, less of them remain in your food.

Innovative cooks have developed alternative methods of intensifying flavor that don't pose all the drawbacks of the traditional long simmer. One trick is to vaporize the liquid in such a way that the pot stays cool enough that the remaining aroma compounds don't degrade. Vacuum evaporation can do this, either with a relatively simple setup (see page 382) or with much more elaborate gear, such as a rotary evaporator (see Distilling the Essence, page 386) or a vacuum concentrator (see How to Reduce Juice in a Vacuum, next page). These versatile tools allow you to make stocks, broths, and other liquids boil cooler than they normally would—even below room temperature.



Reducing sauces the old-fashioned way, with an hours-long simmer, spews some of the most aromatic components into the air and causes chemical reactions that change many of the aromas that remain. Newer approaches minimize or avoid these problems.

Although vacuum evaporation avoids the flavor alterations that high heat causes, it shares with simmering the problem that many of the desirable volatile components are stripped away. The reason is simple: boiling in a vacuum is still boiling, and anything in the container that's more volatile than water will leave first. Concentrating by vacuum distillation, on the other hand, makes it possible to capture the vaporized aromatics and add them back to the concentrated liquid.

Low-Cost Vacuum Reduction

The curious cook can experiment with vacuum reduction techniques at low cost by using a simple **aspiration vacuum system.** This setup requires only a hot plate, a heavy-walled Erlenmeyer filter flask with a high-mounted sidearm port for connecting the flask to a rubber tube, and a faucet aspirator, motorized aspirator, or other vacuum pump that attaches to the other end of the tube (see Reduction in a Vacuum, page 382).

A motorized aspirator vacuum pump used for vacuum reduction will usually work better if you put plenty of ice in the water tank. That's because the water absorbs heat from the recondensing water from the flask. This enables the pump to pull a stronger vacuum.

Vacuum reduction works by lowering the pressure inside the flask. This decrease lowers the boiling point of water (see page 1·294). It also increases the evaporation rate at temperatures below the boiling point. With low enough pressure, you can vacuum reduce at room temperature or less. The limiting factor in vacuum reduction is usually the vacuum pump; it must be able to provide enough suction to keep the pressure in the flask low. This task is not easy because evaporation tends to provide plenty of water vapor (and other volatile gases) to remove. The more powerful the vacuum pump, the lower the temperature at which the vacuum reduction operates.

You can bring precision to the heating process by using a digitally controlled hot plate, preferably one that can be stirred magnetically. A **magnetic stirring bar** placed in the flask will create a vortex, which accelerates evaporation by increasing the surface area of liquid.

Mixing the liquid while it boils also helps you avoid dangerous "bumping," in which large bubbles of vapor form then violently collapse, tossing the flask about the hot plate. These bumps sometimes are violent enough to crack the thick flask.

A vacuum pump for vacuum reduction must be capable of handling copious amounts of water vapor. The simplest solution is to use a faucet aspirator. If water consumption becomes an issue, a motorized aspirator is a good solution.

Aspirator-style pumps are designed to withstand continuous exposure to water vapor and condensation. Other types of vacuum pumps will also work, but make sure that they can resist contact with water vapor. Membrane-type pumps that are intended for use with rotary evaporators or other water-tolerant vacuum pumps are good choices.

Used correctly, vacuum reduction can achieve the effects of classic reduction with liquid solutions whose flavor would change if they were subjected to a higher evaporation temperature. Say that you are making a fruit coulis (a thick sauce) from strawberry or raspberry juice. Conventional reduction methods will give the results a cooked flavor, whereas vacuum reduction preserves more of the delicious raw taste. But, also as in classic stove-top reduction, the most flavorful volatile compounds in the food will evaporate away when a liquid is reduced under vacuum in this way.

HOW TO Reduce Juice in a Vacuum

Vacuum reduction uses a vacuum pump to lower the temperature at which we can evaporate water from a liquid. It is just like conventional reduction, except that the temperature is lower because of the vacuum.

To do this, we need a heat source—a laboratory hot plate with a magnetic stirrer, a vacuum pump, and a filter flask that has a sidearm port that lets us connect to it. The best vacuum pump to use in most cases is either a faucet aspirator or a motorized aspirator. The faucet aspirator is cheap; the motorized aspirator saves water. Other pumps can be used if they can handle a lot of water vapor. Membrane-style vacuum pumps made for rotary evaporators work well. Oil-based vacuum pumps are not suitable because the large volume of vapor will foul them. Remember that every gram of water we reduce from the liquid is going to wind up in the vacuum pump.

1 **Fill a sidearm flask with water to the desired final volume, then mark the water level with a grease pencil, and replace the water with the juice.** This will make it easier to judge when the reduction is complete. If you are going to use a magnetic stirring bar, be sure to measure the level with the bar in the water. Choose a flask large enough to contain the liquid even when it is spun into a vortex by the stirrer. If in doubt, use a larger flask because that increases surface area.

2 **Turn the hot plate on high, typically 300 °C / 572 °F.** It will take 20 min or more to reach this temperature.

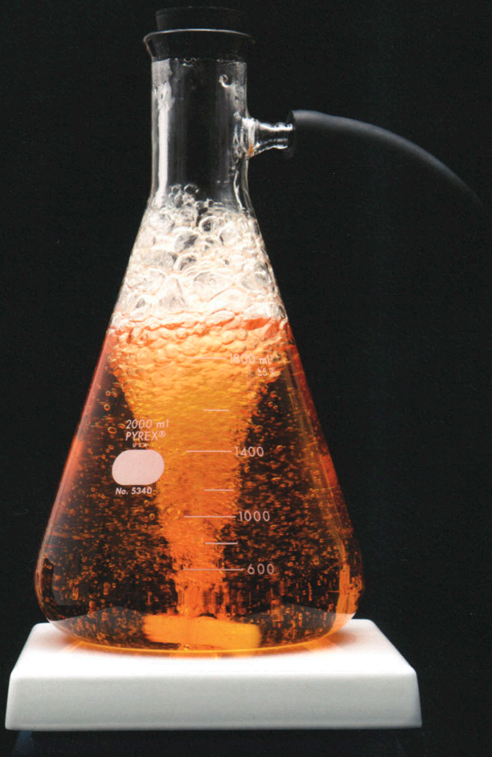
3 **Put a Teflon-coated magnetic stirring bar into the flask, place a stopper in the top, and start the stirrer.** You can vacuum reduce without the stirring bar, but it is better to use one to create a vortex like that shown below.

4 **Connect the vacuum pump to the sidearm of the flask with vacuum tubing, and turn it on.** The pressure in the flask begins to fall. As the vacuum pump runs, the water initially comes to a vigorous boil, but the boil slows as evaporative cooling reduces the temperature of the liquid. The temperature settles at a level governed by the vacuum strength. An aspirator pump usually can keep the boiling liquid to about 35 °C / 95 °F, even with a 300 °C / 572 °F hot plate!

5 **Adjust the hot plate power to attain the temperature needed.** The power required depends on the suction capacity of your vacuum pump. Some trial and error is often needed to find the right balance.

6 **If you are using a motorized aspirator, add ice to the water tank periodically.** Without ice, the hot vapor from the flask will heat the water, thereby raising its vapor pressure and robbing the pump of its suction power. Faucet aspirators or membrane-style pumps do not have this problem, but they waste a lot of water.

7 **Periodically stop the stirrer and check the grease pencil level to determine whether the reduction is complete.**

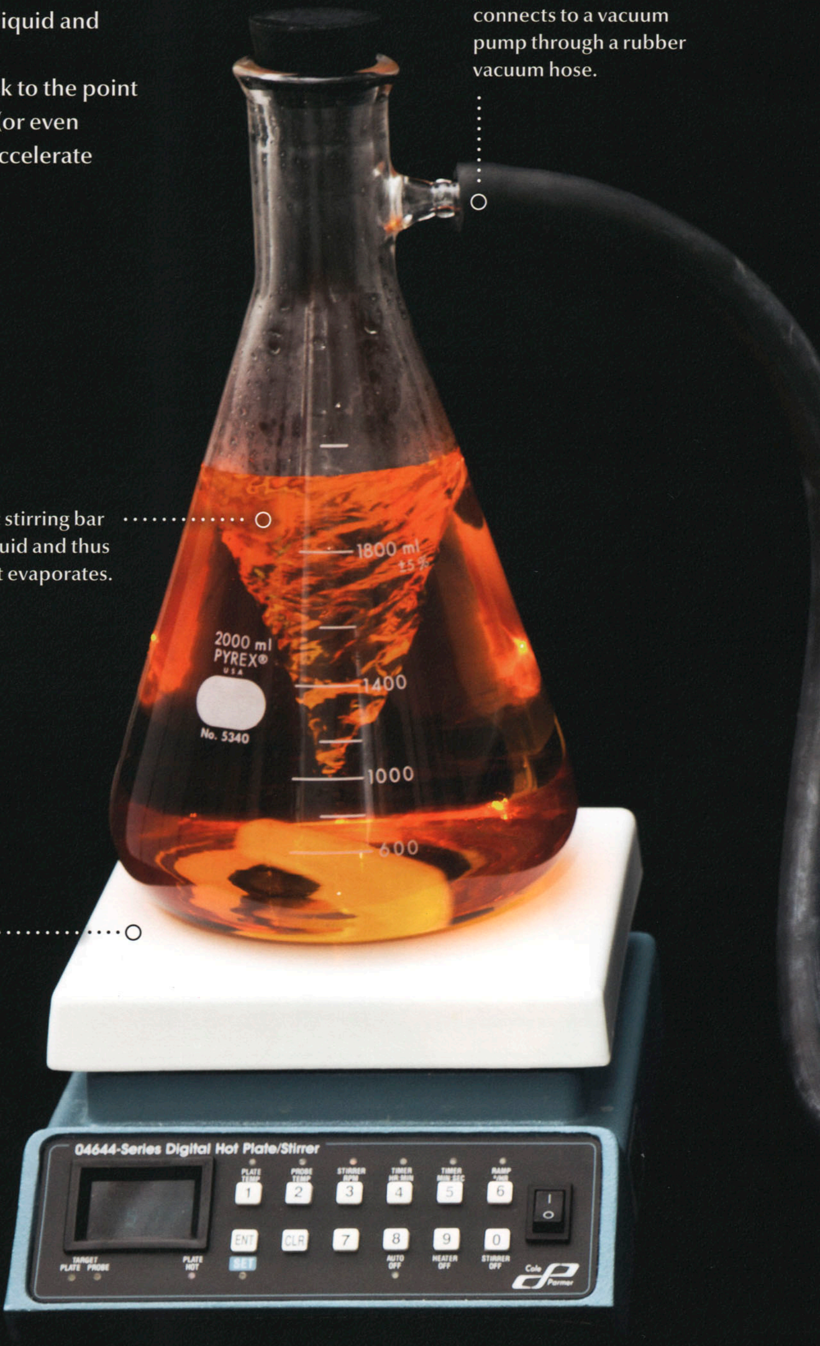


REDUCTION IN A VACUUM

Concentrating the flavors of a sauce, a common procedure in the kitchen, requires cooks to remove much of the solvent, usually water. The most typical approach is to simmer the sauce in a pot and let the water boil off, but the high temperature of a simmer often causes certain undesirable changes to flavor compounds. Apples, for example, don't taste the same cooked as they do raw. Vacuum reduction spares some of the heat-sensitive flavors because it lowers the pressure of the air above the liquid and thus lowers that liquid's boiling point.

The goal is to decrease the air pressure in the flask to the point that the liquid will boil at a lukewarm temperature (or even below it). Stirring the liquid to create a vortex will accelerate evaporation further. The end result is an efficient, low-temperature reduction process.

For more on how pressure affects the boiling point of liquids, see page 1·315.



A sidearm filter flask has a port on one side that connects to a vacuum pump through a rubber vacuum hose.

A vortex produced by the magnetic stirring bar increases the surface area of the liquid and thus speeds the rate at which the solvent evaporates.

With the hot plate turned on, steady-state vacuum reduction will typically occur at about **34** °C / **93** °F. This process will require a lot of heat from the hot plate; it may need to be set all the way to **300** °C / **572** °F to achieve this reduction.

A hot plate with magnetic-stirring capability simultaneously heats the fluid and stirs it to promote evaporation of the solvent. This method uses a laboratory-type digital hot plate that generates a rotating magnetic field, which in turn spins a stirring bar in the flask.

Cooks frequently want to reduce a liquid by a certain amount, but the angled walls of the filter flask make it hard to judge volume by eye. Many flasks have measuring lines indicating specific volumes, but some do not. In the latter case, pour the desired final volume of the fluid into the flask by using water, and mark that target level with a grease pencil.

An aspirator-style vacuum pump is an effective tool for lowering the pressure over the liquid in the flask. This motorized suction device pumps water past an open side port in a tube to produce a pressure drop in the rubber hosing that connects to the flask, in which it creates a partial vacuum. This system recirculates water from a tank so that it doesn't go down the drain. Unlike some other types of vacuum pumps, an aspirator-style pump can handle the ingestion of water vapor.

Pros know that the colder the water in an aspirator pump, the stronger the vacuum. Placing ice (or, for some models, ice plus salt) in the aspirator tank produces a stronger vacuum because it reduces the vapor pressure of water, which increases the evaporation rate. Ice absorbs the heat released by recondensing vapors more effectively than cold water alone can. For the reasons why, see page 1·299.

In the U.S., anyone who distills to create a higher concentration of alcohol must obtain federal and state licenses because the process falls under regulations that cover the production of alcohol. The difficulty of getting these licenses varies from state to state. Some states, such as Oregon, sponsor programs that promote and encourage craft and artisanal distillation, for example. In other parts of the world, you must check with the appropriate local authorities to ensure that your use of distillation equipment is legal.

A rotary evaporator is often called a "rotavap" in labs, but that term is short for Rotavapor, a trademark of Büchi, one of the leading manufacturers. Yamato, Heidolph, IKA, PolyScience, and other manufacturers also produce rotary evaporators.

For more on safe handling of essential oils, see page 324.

The rotary evaporator was invented by Lyman Craig and colleagues and first described in the journal *Analytical Chemistry* in 1950. It was first sold as a commercial product by Büchi in 1957.

The term "fusel oil" is a bit of a misnomer. It is used because the resulting mixture of organic compounds is hydrophobic. But it is not a simple oil like a vegetable oil—it is a complicated mixture of flavor compounds.

The Rotary Evaporator

A more capable but also more complex and expensive refinement of aspiration-type vacuum reduction technology is a **rotary evaporator**. It is a laboratory version of a distillation setup that is able to work at low pressure and temperature. A rotary evaporator lets you hang on to volatile aromatics that escape during conventional vacuum reduction. The sophisticated device evaporates liquid in a spinning flask by gently heating it with a water bath and by lowering the air pressure above the liquid (using a vacuum pump). Unlike simple vacuum reduction, it also condenses and collects the distilled vapor, including the most aromatic elements of fruits, vegetables, and pretty much anything that has an aroma.

A rotary evaporator has just a few primary parts (see Distilling the Essence, page 386). A spherical evaporation flask is cinched into a motorized yoke that spins to increase the surface area and thus speeds evaporation of the liquid by spreading it over the inside surface of the flask. The flask itself sits in a temperature-controlled water bath that provides heat to drive evaporation. Its neck connects through a vacuum seal to a condenser assembly, which chills the vapor, thereby causing some of it to condense into a liquid. The condensates drip down into a collection flask. Situated nearby is a vacuum pump capable of reducing the pressure inside the apparatus by a factor of 100 or so, or from standard atmospheric pressure of 1,013 mbar / 14.7 psi to as low as 10 mbar / 0.15 psi.

The fundamental task of a rotary evaporator is to separate liquids that have different boiling points. Some examples are ethanol, which has a boiling point of 78 °C / 172 °F when pure, and water, which has a boiling point of 100 °C / 212 °F when pure. In a mixture of ethanol and water that is held below 100 °C / 212 °F, more ethanol than water will evaporate.

Note that it is incorrect to say that the ethanol "boils before the water does," as is sometimes stated. A mixture of ethanol and water *has a single boiling point*, which is a complicated function of the proportions and the pressure. It is not the case that the ethanol boils and the water doesn't; both water and ethanol evaporate from the mixture.

If you are at a temperature below the boiling point of pure water and above the boiling point of pure ethanol, however, then *more* ethanol than water will evaporate. For example, a 10% solution of ethanol in water has a boiling point at standard atmospheric pressure of 93 °C / 199 °F. The vapor that it gives off at that boiling point will be about 55% ethanol and 45% water. So if we were to run a rotary evaporator with a 10% ethanol mixture at a temperature of 93 °C / 199 °F, we could concentrate the alcohol from 10% to 55% in a single pass through the machine. If we want a higher concentration, then we need to send the batch through the machine several times.

Note that we use the ethanol example because it is familiar. Distilling 10% alcohol to 55% is similar to what happens when brandy is distilled from wine or whiskey from fermented mash. Making your own spirts is not easy to do with a rotary evaporator, however. First, there are legal issues (see note, above left). Second, the process is very complex because fermented products contain many alcohols and compounds besides ethanol.

Methanol, for example, is usually present in low concentrations as a by-product of fermentation. It has a boiling point of 65 °C / 148 °F, and thus it becomes concentrated mostly in the **foreshots**—the term for the liquid that first boils off and forms a condensate at the start of a distillation batch. In addition to methanol, foreshots may contain acetone and other volatile organic substances that have a lower boiling point than ethanol. The foreshots must be discarded because they can be toxic; they can cause headaches in small quantities and more serious illness, including blindness, at higher doses.

After the foreshots come the so-called **heads**, the **middle run**, and finally the **tails**. Each of these has a different ratio of volatile components. The tails often contain alcohols having a higher boiling point. These alcohols include propyl alcohol, butyl alcohol, amyl alcohol, and furfuryl alcohol and are often called **fusel alcohols** or fusel "oils," which is a misnomer (see note at left). In vodka, fusel alcohols are considered undesirable, and the tails are discarded. In whiskey, the inclusion of some fusels contributes to the characteristic taste.

The art of producing high-quality spirits comes from proper management of the distillation run and optimization of the proportion of heads and tails, which may be separately collected then blended or discarded. Each of these components has a different composition and thus imbues the

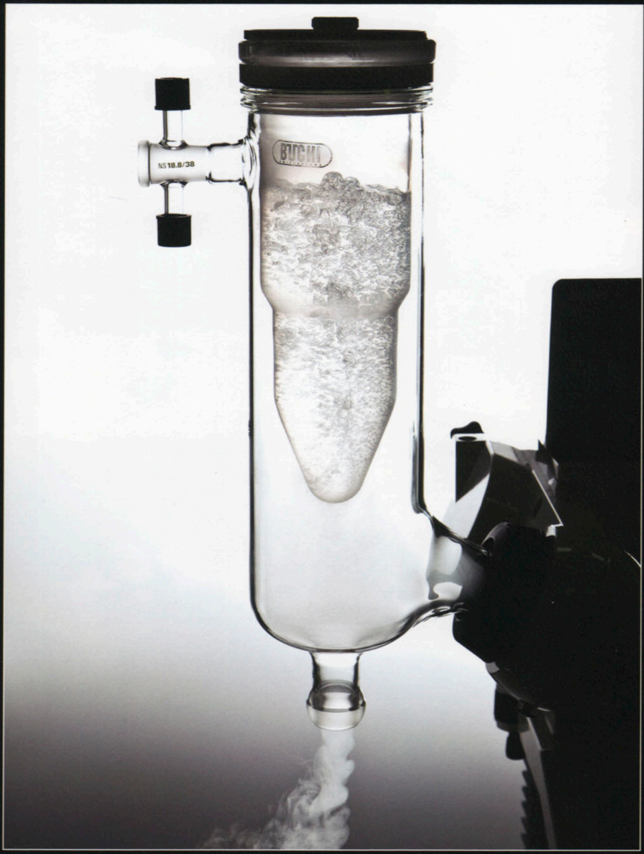
Floral essences can be concentrated in a rotary evaporator. The general rule is that anything you can smell is volatile enough to be distilled.

DISTILLING THE ESSENCE

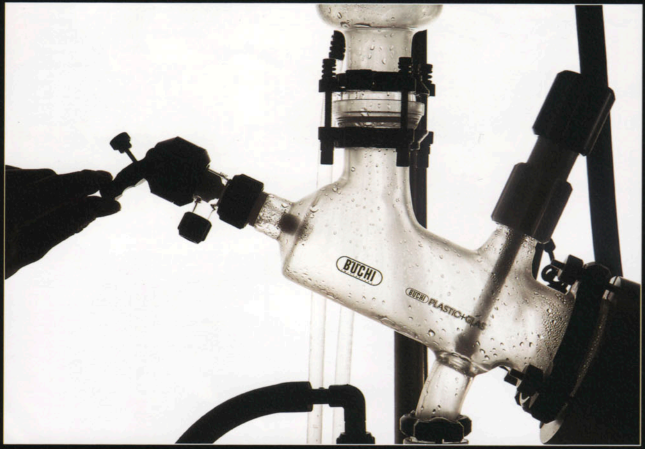
A rotary evaporator is an all-in-one vacuum distillation system for separating liquids of differing boiling points. The rotary evaporator (Büchi's "Rotavapor" model is shown here) is used widely in organic chemistry and biology labs to concentrate by distillation.

In the kitchen, you can use a rotary evaporator to remove a volatile substance and save it in concentrated form—as in the traditional distillation of alcoholic spirits. A rotary evaporator is also handy for removing a solvent so that you can keep the leftover liquid in the evaporation flask, say, to strengthen the flavors of a stock. Chefs also use the machine to extract essences and concentrate liquids at a low temperature to avoid altering the flavor.

You put the liquid mixture to be distilled into the large spherical flask. A water bath then heats the mixture to a controlled temperature from 20–100 °C / 68–212 °F, while an electric motor spins the flask at 20–280 rpm. As the liquid heats and swirls, a vacuum system lowers the air pressure inside the flask to as little as 1% of normal atmospheric pressure. Vapors rise into a cooled system of coiled tubes that condenses some of the vapor phase in a liquid and deposits it into a receiving flask.



A cold trap can use dry ice, liquid nitrogen, or ice mixed with salt to cool the most volatile vapors more effectively than a condensing column can.



The vacuum pump system includes several vacuum joints and control valves from which you can bleed off vacuum when needed. To keep the system free of leaks that can cause the process to fail, you must carefully seal all the joints.

The main control panel lets you immerse the flask into the water bath or lift it out, set the bath temperature, and dial in the rotational speed. Adjust the temperature and the vacuum level to suit the separation that is desired.

The vacuum controller adjusts the pressure of the system. The lower the pressure in the flask, the lower the boiling point of the liquid in the evaporation flask.

The condensing column cools the evaporated solvent and returns it to liquid form. This condenser works by running chilled liquid through coiled tubing that passes through a solvent reservoir. The coolant (usually water) is pumped from a chilling water bath that is held at a low temperature.

You can see the condensate form as droplets on the condensing coil. If the droplets go all the way to the top of the coil, it means you are not condensing all of the vapor. In general you want the droplets to stop forming about three-fourths of the way up the coil. To correct this, lower the temperature of the chilling water in the condenser, increase its flow rate, or do both. Another indicator of incomplete condensation is the odor of vapors coming from the vacuum pump.

A key valve controls the flow of vapor though the main vacuum joint to the condensing column.

The evaporation flask spins to pull a thin coating of the source liquid on the interior of the flask. The film of liquid exposes more of the solvent to the air so that it evaporates much more rapidly.

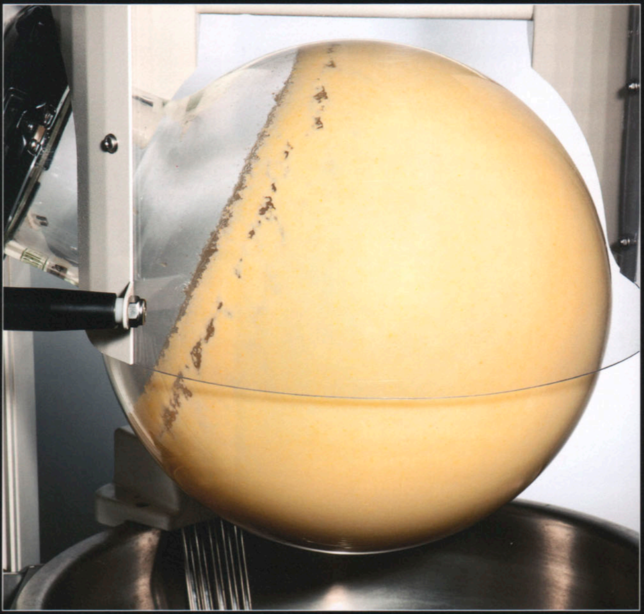
The receiving flask collects the condensate drawn from the condenser. Some rotary evaporators allow you to drain the receiving flask while the system is still under vacuum; others require the machine to be shut down first.

HOW TO Distill with a Rotavap

Distilling delicate scents is challenging because the temperature needed to boil off fragrant compounds at normal atmospheric pressure can alter or even destroy the very fragrances you seek to capture. A rotary evaporator sidesteps this problem by distilling under vacuum at pressures so low that water boils at room temperature.

Modernist chefs, including Heston Blumenthal and Joan Roca, pioneered the use of rotary evaporation for culinary purposes. Blumenthal used it, for example, to distill essence of rosemary so that he could imbue dishes with the smell of a fresh rosemary field on a hot summer day. Roca has distilled compounds as unusual as soil.

In many cases, commercially made essential oils are often better than anything an individual can manufacture. Some ingredients, however, are so commercially insignificant that industrial operations ignore them. A prime example is buddha's-hand citron, an unusual, delicately scented citrus fruit. Here, we show how to distill it.



We do not recommend distilling materials that are not obviously food-grade. A safer approach is to collaborate with a perfumer to re-create the scent with food-grade essences.

1. **Prepare the liquid to be evaporated.** If you are using citrus, remove the outer skin (zest) without including the white pitch or the acidic juice. Mix with vodka (or, optionally, higher concentrations of ethanol); run the mixture through a homogenizer or blender to completely blend its components. Optionally, seal the zest-vodka mixture in a sous vide bag, and place the bag in an ultrasonic bath for 1 h (see page 415).

2. **Place the zest-vodka mixture in the evaporation flask of a rotary evaporator.**

3. **Set the target vacuum to 50 mbar / 38 torr and the bath temperature to 35 °C / 95 °F.** Set the condenser chilling water temperature to 1 °C / 34 °F if you are using a helical condenser. If you are using a cold-trap–style condenser, fill it with ice water, and prepare a salt brine (see page 260). You may have to use a higher bath temperature if the rate of distillation is too slow.

4. **Distill.** The time required depends the size of the batch and many other factors. Check the condensation coil periodically; if the condensation line rises more than three-quarters of the way up the coil, or if you can smell what is being distilled, too many volatiles are escaping. There are several ways to correct this problem. You can decrease the condenser chilling water temperature, increase the flow, or do both. Or you can decrease the bath temperature, but in that case, you must also decrease the vacuum. Release the vacuum when distillation is complete.

5. **Separate the oil from the solvent.** Pipette the thin layer of oil floating on top of the receiving flask into a separatory funnel. Allow the oil to separate overnight, or use a centrifuge (see page 360) to separate the components more quickly.

6. **Drain any solvent from the funnel, then drain the essential oils into a separate vessel.**

7. **Keep the essential oil refrigerated in an airtight container.**

EXAMPLE RECIPE

BUDDHA'S HAND VODKA

Yields 1.5 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Vodka Buddha's hand citron zest	1.5 kg 400 g	100% 27%	① Blend together for 3 min. Optionally, infuse in a sous vide bag or jar placed in an ultrasonic bath for 1 h (see page 302). ② Place liquid in rotary vacuum distiller for 3 h with vacuum pressure at 50 mbar / 38 torr and bath temperature at **35** °C / **95** °F. Set condenser chilling water to **1** °C / **34** °F. ③ Distill.
Distilled water	as needed		④ Dilute distillate to 40% alcohol. Use a hydrometer to measure ethanol concentration.

(2010)

Because we start this recipe with vodka and end up diluting the result to 40% (80 proof) alcohol, no concentration of alcohol occurs. We are simply using alcohol as a solvent for the citrus essential oils.

One can also extract citrus essential oil mechanically, instead of distilling it. Commercially, this is done by pressing; the result is called a pressed essential oil. You can make your own by homogenizing citrus zest and alcohol as in step 1 on the previous page (preferably by treating the mixture in an ultrasonic bath). Then use a centrifuge to separate the oil. It will have a different aromatic quality than the oil produced by distillation.

EXAMPLE RECIPE

VACUUM-CONCENTRATED APPLE AND CABBAGE JUICE

Yields 180 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Green apple juice, centrifuged Red cabbage juice, centrifuged Red wine vinegar	400 g 400 g 400 g	267% 267% 267%	① Combine. ② Set bath temperature to **50** °C / **122** °F, condenser chilling water to **5** °C / **41** °F and target pressure to 50 mbar / 38 torr. ③ Distill. ④ Reserve concentrated source liquid.
Juice concentrate, from above Honey Black peppercorns, finely crushed Salt	150 g 30 g 0.4 g to taste	100% 7.5% 0.27%	⑤ Season.

(2008)

Because we discard the solvent, the concentration can be done by using a vacuum evaporator instead of a rotary evaporator.

Distillation was invented 2,500 years ago in ancient Persia to distill rose water.

final product with its own flavors and qualities. Making spirits is not as simple as running a distillation setup, any more than turning on an oven means you have mastered baking. This is a multifaceted topic that is beyond the scope of this book; we mention it here just to illustrate the complexity of distillation.

The ethanol example was used only to describe separation by distillation. More generally, if you have a mixture of multiple liquids, and each liquid has a different boiling point in its pure form, then the mixture will preferentially evaporate the components with a low boiling point if the temperature is near their boiling points. The trick to using a rotary evaporator is to adjust the pressure, the bath temperature, and the condenser chilling temperature to preferentially evaporate and condense some components and leave others behind. The details depend on the mixture you are dealing with.

Aroma compounds can be smelled precisely because they are volatile and evaporate into the air. This fact means that they have a relatively low boiling point, and they very likely can be concentrated with a rotary evaporator. Foods are almost always complex mixtures of compounds that typically have different boiling points. Finding the right combination of settings (based on an understanding of what happens at the start, middle, and end of distillation) requires some experimentation.

Reducing the pressure by drawing a partial vacuum shifts the boiling point of a liquid (whether pure or a mixture) but does not change the relative order of the boiling points. As you decrease the pressure to below atmospheric pressure, pure ethanol will boil below 78 °C / 172 °F, water will boil below 100 °C / 212 °F, and a 10% mixture of ethanol in water will boil below 93 °C / 199 °F. At any ambient pressure, however, the boiling point of pure ethanol will always be below the boiling point of water at the same pressure. The boiling point of an ethanol–water mixture will also decrease as pressure decreases. The key fact to keep in mind when using a rotary evaporator is that, regardless of the pressure, when an ethanol-water mixture is at its boiling point, ethanol will always evaporate more rapidly than water. Similarly, when a mixture of multiple liquids is at or near its boiling point, the liquids that, in their pure state, have the lowest boiling points will tend to evaporate more rapidly.

Using the vacuum pump, we can lower the boiling point of a mixture of liquids within a wide range—in principle, all the way down to 0 °C / 32 °F. The main reason to lower the boiling point is to preserve the quality of heat-sensitive flavor compounds that would be cooked or altered at higher temperatures.

The condenser portion of the rotary evaporator condenses out the vapors. Sometimes this is the desired product; we keep the condensate and throw out the remnants in the evaporation flask. That is typically what is done in making spirits where the final product is the condensate. In other cases, we want to remove a solvent, so we

Fresh watermelon juice, before and halfway through vacuum concentration in a Genevac Rocket. The delicate flavor of watermelon juice is retained even as water is removed. This concentration could also be done in a rotary evaporator (see page 384) or by vacuum reduction (see page 380).

throw away the condensate and keep what is left in the evaporation flask. Vacuum reduction can be done in a rotary evaporator; in that case, you are mostly evaporating then condensing water. A more complicated case is one in which you run the rotary evaporator with a fruit or floral juice first at low temperature (below the boiling point of water) to condense and save volatile flavor compounds. Once these are saved, the temperature can be increased to evaporate water and concentrate the liquid. Then the saved volatile compounds from the first step can be mixed back in.

A leading maker of rotary evaporation equipment, Büchi Labortechnik of Switzerland, recommends that you first choose a temperature for the boiling point of the solvent or material you want to distill. The bath temperature should be set at least 20 °C / 36 °F higher than the boiling point. The temperature in the condensing column should be set at least 20 °C / 36 °F lower than the boiling point. These values are a good rule of thumb; specific cases may need different values.

As an example, if you are distilling to recover ethanol, then you can set the vacuum to 167 mbar / 125 torr to place the boiling point at 40 °C / 104 °F or higher (see table below). The bath temperature would be 60 °C / 140 °F, and the condenser chilling temperature set to 20 °C / 68 °F or lower. You could place the boiling point higher, or lower, by adjusting the vacuum accordingly.

The condenser is kept cold by chilled liquid pumped through it. The typical source is a chilling water bath (see page 238). A chilling water bath can supply the condenser with 1 °C / 34 °F water. If brine or antifreeze is used in the chilling bath, the temperature can be decreased to below 1 °C / 34 °F. Additional cooling enlarges the temperature difference between the water bath and the condenser tube, which enables the system to recapture more of the volatile aromatics. If a larger temperature difference is required, a cold-trap-style condenser can be used with a slurry of dry ice and acetone or with liquid nitrogen as the chilling agent for even more effective separation. Depending on the situation, you may want to keep all of the volatiles and use the coldest possible condenser temperature, or you may find that a higher condenser temperature works better.

Care needs to be used because distilling the essences of some things can create a toxic result. Distilling the essence of leather may seem compelling, but the product will include toxic chemicals used to tan the leather. Even fully edible products can yield a dangerous result because extreme concentration makes their essential oils harmful.

Users should also know the laws and regulations in their local, state, and national jurisdictions that pertain to the ownership and operation of distillation equipment, particularly if the result is a liquid with a higher alcohol concentration than the one you started with.

Genevac's Rocket

The rotavap may strike many as rather high-tech for a kitchen, but there is another precision instrument that is even further out on the bleeding edge of culinary technology. Genevac, Ltd., of Ipswich, England, has made an elegant alternative to fill some uses of the rotary evaporator. This device is called the Rocket Evaporator. The Rocket is especially adept at concentrating highly aromatic and heat sensitive solutions so gently that the flavor remains pristine even after massive concentration.

The research team at The Fat Duck restaurant has pioneered the culinary uses of this sophisticated device, which combines variable vacuum pressure, steam-based temperature control, and low-speed centrifugation. At the lowest pressures that the Genevac Rocket can attain (6 mbar / 4.5 torr in the 2010 model), water boils even at

Boiling Point vs Vacuum Pressure

To set your rotary evaporator, choose a temperature appropriate for the boiling point of the solvent or material you want to distill, and then adjust vacuum pressure accordingly.

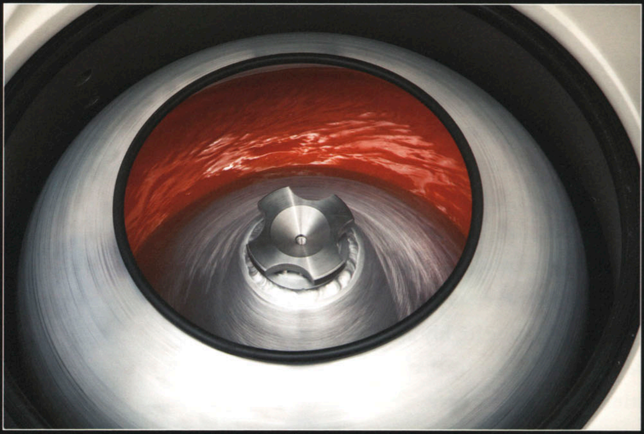
Boiling point		Water		Ethanol	
(°C)	(°F)	(mbar)	(torr)	(mbar)	(torr)
20	68	23	17	58	44
30	86	42	32	102	77
40	104	72	54	167	125
50	122	120	90	289	217
60	140	194	145	463	347

ROCKET SCIENCE

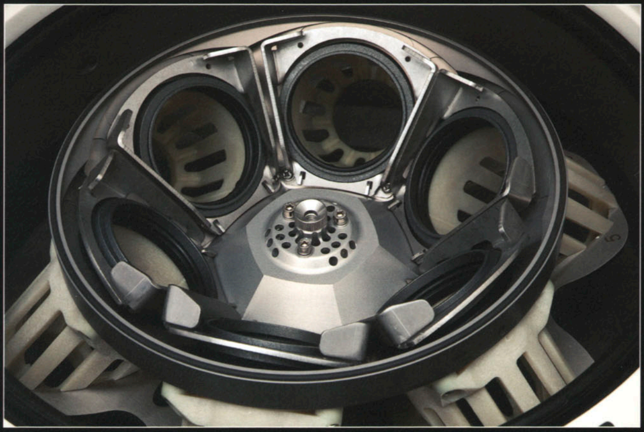
The Rocket centrifugal evaporator, made by Genevac, is an all-in-one-device that spins and concentrates fluids at the same time that it removes solvents from solutions at low temperatures. Its wide range of capabilities makes it useful for cooks who want to intensify the flavor of a liquid or extract an essence. Although this lab-quality instrument carries a steep price, it provides a convenient way to do vacuum reduction while capturing distilled volatile compounds.

The centrifuge in the Rocket spins the solution to expand the surface area of the liquid being condensed and to prevent it from violently "bumping" as it boils. Like a rotary evaporator, the device lowers the air pressure above the fluid for low-temperature evaporation. Because temperatures stay low, heat-sensitive flavors, aromas, and pigments remain intact.

Also like a rotary evaporator, the Rocket can condense whatever solvent (usually water) and volatile aromatics it removes from the original solution. Unlike a rotary evaporator, the Rocket can also serve as a low-speed centrifuge, thus giving it extra utility in the kitchen.



An eight-liter bucket is a design option for concentrating large batches at once.



The standard rotor holds six bottles. Each bottle contains a different solution, but they all must be properly balanced.

1 **Fill and balance bottles as you would for a centrifuge (see page 363).**

2 **Place matched bottles across from each other in the rotor.** Engage the machine.

Low-temperature, low-pressure steam heats the flasks to accelerate the evaporation of the liquids. The device maintains a preset temperature with high precision.

The cooling coil condenses the solvent from vapor back to liquid—a very useful feature if the solvent is something that you want to save, such as alcohol or another valuable volatile.

The rotor spins the liquid slowly in six bottles. The motion keeps the boiling samples from bumping during distillation or concentration. For large batches, replace the carousel with an optional bucket, which contains up to 8 l / 8 qt of solution.

A membrane vacuum pump lowers the pressure of the air above the liquids in the bottles. A chiller in the chamber keeps the liquids in the flasks cool.

temperatures below its freezing point. That's the kind of high performance that research scientists might need to protect fragile biological compounds, but it also empowers the Modernist cook to attempt new flavoring possibilities.

The source solution goes into a half dozen pint-sized bottles of solution that fit into a rotor that the Rocket spins at high speed. A condenser collects the vaporized solvent and leaves the flavorful and often intensely colored concentrate behind.

What is perhaps most remarkable about the Rocket is the way that it merges, in one unit, the virtues of several appliances often found in Modernist kitchens. In addition to having a distillation-condensation system similar to a rotary evaporator, the Rocket vacuum concentrates with a low-temperature, steam-based heater under precise temperature control—and it includes a low-speed centrifuge that can handle many culinary spin jobs.

The designers of the machine cleverly ensured that centrifugal forces would prevent the solution from "bumping" and boiling over in the containers, a usually common problem when liquids are subjected to a vacuum. Unlike a rotary evaporator, this machine can distill up to six different liquids simultaneously, although the volume of each one produced is quite small. Also very useful is the device's ability to store and replace programmed operations. Once you work out the process conditions that give you the results you want, you can just hit a button to recall them for a new batch and walk away.

All that performance comes at a steep cost: tens of thousands of dollars as of this writing, although Genevac reportedly has more affordable designs under development for kitchens.

For more on the freeze concentration process used in the recipe below, see page 396.

EXAMPLE RECIPE

MOCK TURTLE SOUP ADAPTED FROM HESTON BLUMENTHAL

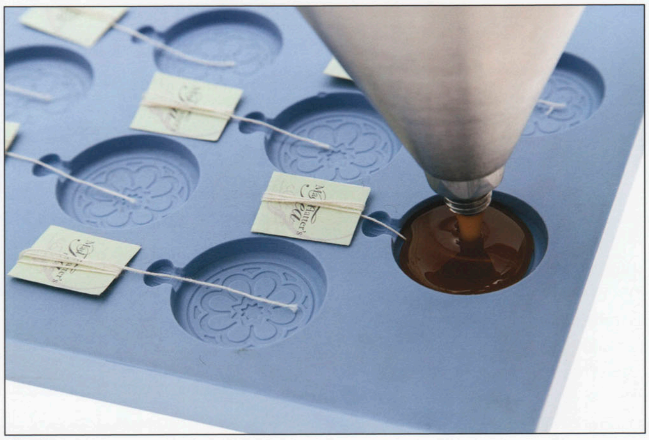
Yields 4 kg (about 90 servings)

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Brown beef stock see page 301	1 kg	200%	① Gently warm stock until no longer gelled but still cool. ② Add cherry tomatoes, and infuse at room temperature for 20 min. Strain, and reserve infused stock.
Cherry tomatoes, quartered	120 g	24%	
Mushroom jus see page 344	290 g	58%	③ Combine, and mix with infused stock. Vacuum seal, and freeze. ④ When frozen, remove from bag, and place on perforated tray lined with double layer of cheesecloth. ⑤ Refrigerate, while freeze-filtering for 72 h (see page 370). ⑥ Vacuum seal filtered stock, and freeze. ⑦ Transfer frozen stock to food processor; pulse until coarsely crushed. ⑧ Drain crushed, frozen stock over fine sieve lined with double layer of cheesecloth. ⑨ Collect thawed, concentrated stock, and discard remaining ice. ⑩ Transfer concentrated stock to Genevac Rocket bottles, and reduce by half at 8 mbar / 6 torr, heating temperature of 50 °C / 122 °F, and condenser at 1 °C / 34 °F. ⑪ Reserve 500 g of reduced stock.
Fino sherry	165 g	32%	
White soy sauce	133 g	26%	
Freeze-concentrated stock, from above	500 g	100%	⑫ Combine, and vacuum seal. ⑬ Cook in 60 °C / 140 °F bath until all gelatin dissolves, about 5 min. ⑭ Transfer to depositing funnel, and dispense 6 g into each pocketwatch silicone mold. ⑮ Refrigerate, and allow to set completely, about 4 h.
Gelatin, 160 Bloom	60 g	12%	
Gold leaf sheets	as needed		⑯ Remove gelled stock from molds, and place flat side down on corner of gold leaf sheet. Use tweezers to gently fold gold leaf over top of each gelled stock portion; use fine brush to tuck gold leaf under bottom edges. ⑰ Refrigerate until needed. ⑱ To serve, place each stock portion in bottom of teacup; pour 40 g of hot water over stock. Stir until gelled stock dissolves.

(original 2009, adapted 2010)

10a

10b



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The slower and larger the ice crystals grow in the freezing solution, the greater the concentration of the remaining liquid. That's just the opposite of what is needed to make good ice cream, in which rapid freezing forms smaller ice crystals and thus a much smoother product.

Freeze concentration to make ice wine was known to the ancient Romans and was mentioned by Pliny the Elder.

Freezing out the Good Stuff

Just as some liquids have different boiling points, they also have different freezing points, and that difference can be used to preferentially concentrate them. One traditional method of making applejack—a form of apple brandy—is to freeze-concentrate hard apple cider. The process of **freeze concentration** was known as jacking. The process, which is also called fractional freezing or freeze distillation, has been used in many other contexts.

Freeze concentration exploits a phenomenon called freezing-point depression (see page 1·304). Pure water freezes at 0 °C / 32 °F, but dissolved solutes, including salt, sugar, alcohol, and flavor compounds, lower the freezing point. When a solution freezes, relatively pure ice crystals grow. Their growth takes water out of solution and leaves the solutes behind, thereby increasing their concentration in the remaining liquid.

One of the earliest uses of freeze concentration was in making ice wine (or *eiswein* in German)—wine pressed from grapes that are partially frozen during pressing. The freezing helps concentrate sugars in the grapes, thereby leading to extra sweet juice and very sweet wine.

Natural ice wines are produced only in years when weather during harvest is cold enough to freeze the grapes. These wines tend to be made mainly in northerly or high-altitude wine-growing regions such as Germany, Austria, and Canada, which has recently become the world's largest producer of ice wines. In most wine-making countries, only natural ice wines can be labeled "ice wine."

Winemakers quickly realized that they didn't need to wait for winter and could freeze the grapes themselves. This process is called cryoextraction and may be used in making any type of wine to increase its sugar content.

Ice beer is another form of freeze concentration. Ice beer is cooled until ice crystals form, and these crystals are then filtered out. The resulting beer often has a alcohol content that is higher than usual.

Freeze concentration cannot achieve high concentration ratios or a very pure result. During this process, some solutes get incorporated into the ice or trapped by ice crystals, and the separation does not work perfectly. But it does have the advantage of retaining even very volatile substances because it does not include evaporation.

Freeze concentration works best when ice crystals can grow slowly because that favors the growth of large crystals that are mostly water. Slow freezing can be accomplished in a freezer or by using an ice brine (see How to Freeze Food in a Salty Brine, page 260). Once the ice crystals have formed, they can be removed with a filter, a fine sieve, or a separatory funnel.

Reverse Osmosis

Perhaps the most exotic technique for concentrating flavors is one that has gained wide use in commercial winemaking. Known as **reverse osmosis**, the process relies on forcing a solution that contains dissolved components, such as proteins, salts, and sugars, through a semipermeable polymer membrane. The membrane is engineered to have uniform pores through which only the water molecules can pass. It takes high pressures, from 2–69 bar / 30–1,000 psi , to push the liquid through the membrane. The most common use of reverse osmosis is in purifying water. In that case, you keep the pure water that passes through the membrane (see page 1·335).

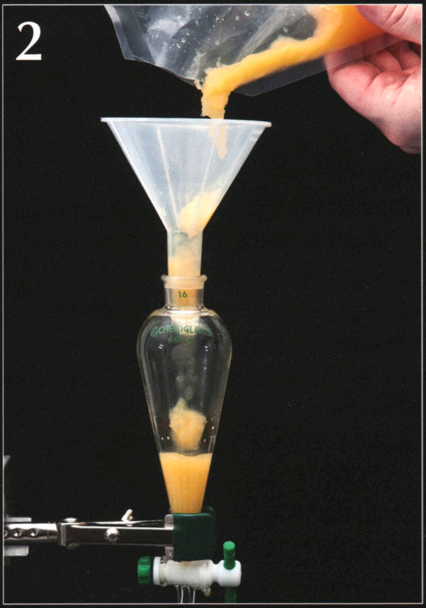
Vintners use reverse osmosis to remove water from grape juice; they discard the pure water that passes through the membrane and keep the "dirty" part—the intensely flavored, concentrated juice—which they then transfer to the fermenters.

This pressure-driven filtering technique has great potential for restaurant kitchens as well, where it could be used to concentrate juices, stocks, and other liquids. Reverse osmosis yields liquids enriched in everything a cook wants to save but does not require destructive heat or result in the losses that come with evaporation.

Although reverse-osmosis technology is not inherently expensive, it can be cumbersome to use. An innovative appliance vendor and some time will probably be needed to scale down the process before commercial units can appear in kitchens.

HOW TO Freeze Concentrate

The objective of freeze concentration is to create as many pure ice crystals as possible then to drain away the unfrozen, concentrated liquid. The solutes for freeze concentration need to have a lower freezing point than that of pure water. Salt, sugar, and alcohol are examples that work well. Unfortunately, this technique is slow and can concentrate by only about 40%, but because there is no evaporation, the results are remarkable.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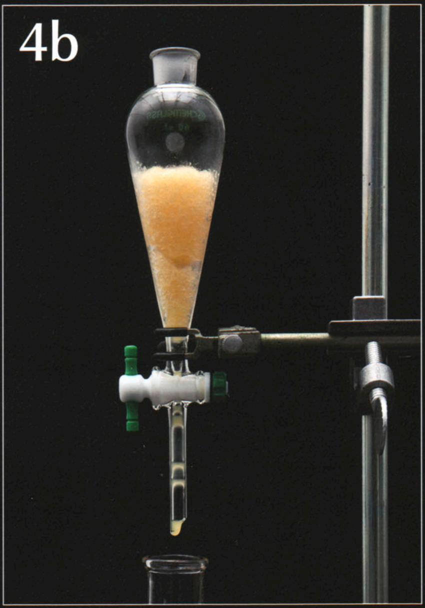
4a


4b

1 **Freeze the liquid slowly, stirring occasionally to achieve a slushy consistency.** To do this in a sous vide bag, place the bag in the freezer and massage it periodically.

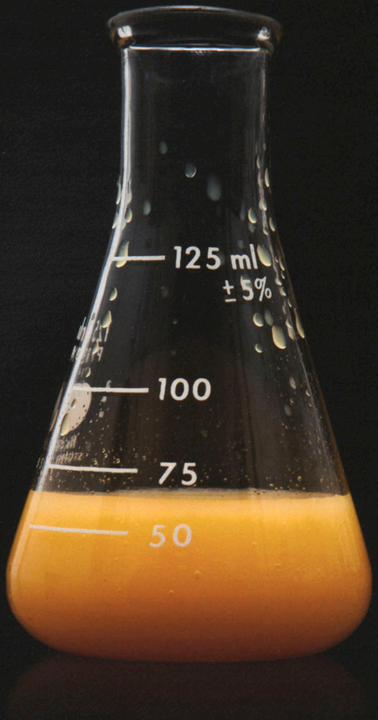
2 **Pour the slush into a separatory funnel.** Alternatively, simply add the unfrozen liquid directly to the separatory funnel.

3 **Nestle the filled, sealed funnel in an ice-brine bath to create as many ice crystals as possible.** Agitate the funnel occasionally to ensure that the liquid remains slushy instead of solid. Freeze until the liquid is a coarse, frozen slush.

4 **Set the funnel in a ring stand, and let the juices settle.** When there is a visible division between the ice crystals on top and the juice or liquid on the bottom, open the stopcock on the funnel, and drain out the liquid. Discard the ice.

For more on making an ice brine bath, see page 260.


3



CUTTING 'EM DOWN TO SIZE

It's not exactly a love-hate relationship, but as much as we love our food, there are times that we want to pulverize it. Any cook does—ingredients are often more interesting to eat or easy to cook when broken into lots of tiny pieces. Both heat and flavor components flow more readily through little bits, so they cook faster and yield a greater amount of the good stuff. It's more efficient to mix, dissolve, and transfer flavor among several ingredients if they are first cut down to size. And particle size can largely determine the texture of any food that flows, whether it be a chunky salsa prepared using knives and a few pulses of a blender, or a silky smooth lentil soup pushed through an ultrafine sieve.

For more on making oil-water and water-oil emulsions, see chapter 15 on Emulsions, page 4·196.

It takes a lot more energy to cut food into tiny pieces than it does to chop that food into big chunks. A knife is not always the most efficient tool for the task, and even the most skilled prep cook can slice and dice only so finely and quickly.

To speed the job and get to smaller sizes, a kitchen blender, food processor, whisk, hand beater, or mortar and pestle come in handy. At some stage, these conventional kitchen tools also reach their limit: you keep running the blender or moving the mortar, but the food just doesn't get any smaller; at most, all that happens is that the machines and their contents grow warmer.

Blending generates heat, so even when a blender can reduce food particles' size no further, it will slowly heat food. This is usually an annoyance, but it can be useful for cooking foods, such as egg custard, in situ.

This is the point at which the sophisticated equipment of the Modernist kitchen comes in, including Pacojets, colloid mills, sonicators, and ultrahigh-pressure homogenizers. These tools may sound a little intimidating, but they are easier to use than you might think. Although they rip apart foods using the same basic compressive, impact, and shear forces at work in a knife, sieve, grater, or mallet, these newer tools can pulverize or mix food to a degree far beyond what traditional means can achieve. They thus greatly expand the range of particle sizes available for use in your recipes and open new vistas of flavor and texture.

The word "particle" may conjure images of only solid foods, but liquids come in particles, too—most notably in the form of emulsions, which are liquid mixtures of tiny droplets (i.e. particles) of immiscible liquids such as oil and water. Making an emulsion presents its own size-reduction challenges, whether you are blending oil into water (as in milk, mayonnaise, and vinaigrettes) or the other way around (as in butter or margarine). Although it may not take as much energy to split colloidal globules into smaller droplets as it does to, say, grind chestnuts into chestnut butter, it does take both energy and advanced equipment to make the finest, smoothest, and longest lasting emulsions. A whisk is not always sufficient.

The amount of energy required for a particular application—and thus the tool that is best suited for the job—depends on the texture of the food you are starting with and the texture you want to achieve. Is it hard or soft, wet or dry, granular or fibrous in structure? Hard foods, for example, tend to have crystalline or brittle amorphous microstructures (like glass), so they shatter when you slice them. Soft foods, in contrast, often cleave and split along innate contours defined by the fibers or cells inside them.

The fundamental principle to keep in mind is that the amount of power that goes into reducing the food chunks is inversely proportional to the

A colloid mill is one of the most powerful and flexible tools for grinding food into a smooth puree.

STRATEGIES FOR GRINDING, MILLING, AND PUREEING

When you want to break food down more finely than is possible with a knife, turn to more specialized tools ranging from the primitive mortar and pestle to the superpowerful, technologically advanced Pacojet. A household blender or food processor excels at making a basic puree, but these devices have limited power. The next step up is a rotor-stator homogenizer, the ideal tool when the mixture starts out smooth and your goal is to make it silky or as superstable as an emulsion. The most unusual tool is the Pacojet, which can make remarkably fine powders and pastes from virtually any ingredient that can be packed in a canister and frozen. This table lists the tools from lowest to highest power.

	Applications						
Strategy	Coarse paste or powder	Thin puree	Thick puree	Fine powder	Fine puree	Note	See page
mortar and pestle	✓	✓	✓			produces a wide range of particle sizes; hard work	
food mill	✓		✓			suitable only for soft foods	401
coffee grinder	✓			✓		high shearing force; good for grinding spices	4·376
household blender	✓	✓				medium shearing force, fine for most fluids but not for thick purees	412
ultrasonic homogenizer					✓	both stabilizes emulsions and releases volatile compounds; useful for extractions and very fine emulsions	415
food processor	✓		✓			better than a household blender for large, coarse items	412
commercial blender		✓	✓		✓	higher shearing force than a household blender	412
rotor-stator homogenizer		✓			✓	makes silky purees and very stable emulsions when starting from fine particles; expensive	420
ultrahigh-pressure homogenizer					✓	ideal for stabilizing emulsions; very expensive; must start with moderately fine puree	422
Pacojet	✓	✓	✓	✓	✓	very high shear force purees most solids; expensive; must start with frozen food	408
colloid mill	✓	✓	✓	✓	✓	large footprint; requires cooling during use; can easily make smooth purees from the toughest foods; good for large volumes	416

size of the resulting pieces—more power yields smaller bits. That is equally true for the globules in an emulsion as it is for the shards of a solid. Because Modernist chefs often want to make silky smooth sauces or nearly indestructible emulsions, their kitchens often sport grinding machines more typical of industrial settings.

At the business end of a food mill, for example, are surfaces that apply much stronger shear forces to the food passing through the mill than the blades of the most powerful electric hand beaters can generate. Food mills are thus able to knock particles down to just a few microns (millionths of a meter, or 40 millionths of an inch) across, smaller than the human tongue and mouth can discern as individual grains. As far as perception goes, solids that are this fine feel as smooth as liquids.

Keep in mind, however, that no size-reduction procedure ever yields particles that are all exactly the same size. To constrain the range of sizes, run each batch through the machine several times. The more runs, the more uniform the texture.

Dry Grinding

For breaking up hard and rigid foods such as dried grains and spices, the cook's strategy hasn't changed much in many millennia: grind and mill the food into progressively finer particles. This traditional approach was probably originally inspired by the way in which eaters' teeth slice and crush foods when they chew. Early tools such as stone blades, mortars and pestles, and millstones worked in much the same way as molars and bicuspids.

Today, you can choose among a wide variety of food- and grain-milling machines that feature an assortment of blades, hammers, and shearing tools. Each device specializes in processing foods that have a certain starting texture or range of sizes into smoother or smaller forms.

Probably the most familiar grinding device in the kitchen is the countertop coffee grinder, whose whirring blades chop food more finely the longer it runs—up to a point. **Burr grinders**, a category that includes old-fashioned, hand-cranked models as well as motorized espresso grinders, work differently. They crush coffee beans or other foods between two surfaces that rotate relative to one another, creating a shearing motion that tears the food apart. A burr grinder yields more uniform particles than a comparable blade grinder. It is a good tool for processing coffee beans, seeds, and hard spices, including cinnamon, nutmeg, and pepper.

Ball mills resemble burr grinders but crush foods between the hard surfaces of continuously moving steel spheres. Industrial firms use ball mills to produce powdered pigments and other fine particulate products.

Ball mills and other dry grinding tools are mainly used industrially. Small-scale laboratory units are used in scientific research, but we have not found good kitchen applications for them.

THE MATHEMATICS OF
The Power to Pulverize

Engineers who work in the food-processing industry often rely on a special set of equations that helps them determine how much energy is required to perform a particular size-reduction task. Among these is Kick's law, which provides practical guidance for coarse-grinding processes that increase the material's surface area by only a relatively small amount. Kick's law states that the energy needed to conduct the grinding is proportional to the length (i.e., the longest dimension) of the pieces before grinding, divided by their length after grinding. This equation works well when this reduction ratio is no greater than about eight—meaning the bits end up no less than than one-eighth of their starting size.

Rittinger's law provides more accurate estimates of the energy needed for degrees of size reduction that are much greater than Kick's law can handle. Rather than involving a single typical dimension of the pieces, Rittinger's law instead relates the energy to the change in surface area from beginning to end.

For processes that fall in between very coarse and very fine, Bond's law sometimes works best. It bases calculations on the pore size of a sieve that will allow 80% of the beginning materials to pass, as well as the pore size that will allow 80% of the final product to pass.

The classic kitchen pepper grinder is an example of a burr grinder. The same approach is also used in high-quality coffee grinders for espresso making (see page 4·376).

EXAMPLE RECIPE

CHILI TOMATO SPICE BLEND

Yields 70 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Freeze-dried tomatoes see page 451	30 g	100%	① Grind together to fine powder. ② Store in airtight container until needed.
Freeze-dried piquillo pepper see page 451	25 g	83%	
Coriander seeds, toasted and ground	5 g	16.7%	
Sweet paprika powder	5 g	16.7%	
Controne hot pepper, finely ground	2 g	6.7%	
Hot-smoked paprika powder	1 g	3.3%	
Saffron threads	1 g	3.3%	
Fennel seeds, toasted and ground	0.6 g	2%	
Ajowan seeds, toasted and ground	0.5 g	1.7%	

(2010)

EXAMPLE RECIPE

INDIES SPICE BLEND ADAPTED FROM OLIVIER ROELLINGER

Yields 20 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Coriander seeds	2.1 g	28%	① Combine and toast in frying pan until fragrant.
Black peppercorns	1.7 g	22.7%	② Remove from heat, and cool.
Caraway seeds	1.5 g	20%	
Cinnamon stick, grated	1 g	13.3%	
Mace	1 g	13.3%	
Sichuan peppercorns	1 g	13.3%	
Star anise	0.4 g	5.3%	
Clove	0.2 g	2.7%	
Turmeric powder	7.5 g	100%	③ Combine in coffee grinder with toasted spice blend.
Orange peel, grated	2.5 g	33.3%	
Vanilla seeds and pulp	1.5 g	20%	④ Grind to fine powder.
Cayenne pepper	0.5 g	6.7%	⑤ Store in airtight container until needed.

(original 2001, adapted 2010)

Most Indian recipes start with toasting spices in a dry frying pan to develop the flavor. A better way to toast spices is to put them in a shallow pan in a combi oven or convection oven at 170 °C / 338 °F until fragrant. This avoids scorching the spices.

To make the vanilla seed-pod scrapings, split a vanilla bean lengthwise with a knife then scrape the seeds and the residue surrounding them from the seed pod.

EXAMPLE RECIPE

QUATRE ÉPICES

Yields 420 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Black peppercorns	200 g	100%	① Toast spices in a dry skillet until fragrant.
Cinnamon, ground	100 g	50%	② Combine in coffee grinder and grind to fine powder.
Nutmeg	80 g	40%	
Cloves	40 g	20%	③ Store in airtight container until needed.

(2009)

A colloid mill can be used instead of a coffee grinder for large batches of spice mixtures (see page 416).

So many other kinds of mills exist that you could fill an entire catalog with them. Both **single- and double-disc mills** rely primarily on strong shear forces, whereas **pin-and-disc mills** add the punch of impact as well. **Roller mills** reduce particle size by using a combination of shearing and compressive forces. **Colloid mills**—which we discuss below because they also work on liquids—use jagged, spinning teeth and come in industrial sizes that possess fearsome power.

Some varieties of milling equipment have been tailored to make specific foods. Chocolate was unappetizingly gritty—and thus usually consumed in beverages—before the Swiss confectioner Rudolph Lindt invented the conche machine in 1879. Lindt's system uses rollers to grind cocoa, sugar, and other ingredients to sizes too small for the tongue to register, while simultaneously heating and aerating the mixture to remove off-flavors and to ripen the desirable tastes that remain. This process is called **conching** and has become fundamental to chocolate making.

EXAMPLE RECIPE

CITRUS SPICE ADAPTED FROM HESTON BLUMENTHAL

Yields 30 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Orange zest, finely grated	11 g (from two oranges)	100%	① Combine. ② Spread on silicone baking mat. ③ Dehydrate at **50** °C / **120** °F until completely dried, about 35 min.
Lemon zest, finely grated	9 g (from two lemons)	82%	
Lime zest, finely grated	3 g (from two limes)	27%	
Licorice root, finely ground	3 g	27%	④ Combine with dried zest and grind to fine powder. ⑤ Vacuum seal and refrigerate until use.
Vanilla seeds and pulp	1.5 g	13.6%	
Coffee beans, roasted and finely ground	1 g	9%	
Coriander seeds, deeply toasted and finely ground	1 g	9%	
Mint leaves, freeze-dried see page 3·372	1 g (20 leaves)	9%	

(original 2004, adapted 2010)

EXAMPLE RECIPE

LICORICE POWDER ADAPTED FROM MICHEL BRAS

Yields 280 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Black olives, pitted	400 g	250%	① Arrange on nonstick baking sheet in one even layer. ② Dehydrate in 80 °C / 175 °F oven for 8–12 h until completely dried. ③ Measure 160 g of dried olives.
Dried black olives, from above	160 g	100%	④ Grind together to fine powder (N-Zorbit M will prevent powder from turning into paste), and reserve.
N-Zorbit M (National Starch brand)	20 g	12.5%	
Almond powder (meal)	80 g	50%	⑤ Mix together, and spread on nonstick baking sheet. ⑥ Bake in 135 °C / 275 °F oven until light golden, about 35 min, and cool. ⑦ Blend into olive powder.
Demerara sugar	10 g	6.25%	
Licorice root, finely ground	5 g	3.1%	⑧ Stir into powder.
Salt	5 g	3.1%	
Tonka beans, finely ground	1 g	0.625%	

(published 2002, adapted 2010)

EXAMPLE RECIPE

RAS EL HANOUT

Yields 155 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Ginger powder	40 g	100%	① Dry-blend together. ② Vacuum seal, and refrigerate until use.
Turmeric powder	30 g	75%	
Black peppercorns*	25 g	62.5%	
Coriander seeds*, toasted	15 g	37.5%	
Grains of paradise*, toasted	12 g	30%	
Cinnamon stick*	5.5 g	13.75%	
Star anise*, toasted	5.5 g	13.75%	
Dried chili*	5.4 g	13.5%	
Dried rosebuds*	5 g	12.5%	
Allspice*	4 g	10%	
Cubeb pepper*, toasted	3.6 g	9%	
Clove*	2 g	5%	
Nutmeg*	2 g	5%	

(2010) *(*finely ground*)

EXAMPLE RECIPE

EXOTIC SPICE MIXTURE INSPIRED BY OLIVIER ROELLINGER

Yields 90 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Sesame seeds	50 g	100%	① Combine, and toast in frying pan until golden. ② Cool completely, and reserve.
Cumin seeds	8.2 g	16.4%	
Sumac	18 g	36%	③ Grind together in spice grinder. ④ Add sesame and cumin blend, and grind to fine powder. ⑤ Store in airtight container until needed.
Ajowan seeds	6.5 g	13%	
Dried oregano	2.9 g	5.8%	
Cardamom seeds	2 g	4%	
Ground cinnamon	2 g	4%	
Nutmeg, freshly ground	1.5 g	3%	

(2001)

Pacotizing

Many Modernist cooks have adopted an unusual pureeing tool, called the **Pacojet**, with such enthusiasm that a new verb—pacotize—has entered the culinary lexicon. Unlike almost all other size-reduction machines, the Pacojet specializes in grinding frozen material. The maker, Pacojet AG of Zug, Switzerland, originally designed the machine to make ice cream and sorbet (a task at which it excels), but innovative cooks have learned to use it for general fine-grinding jobs. The Pacojet is the only kitchen device capable of making frozen powders, an innovation introduced into fine cuisine by Ferran Adrià of elBulli.

Using a Pacojet is a fairly straightforward operation (see Sorbet (or Powder) in a Flash, page 408). You place the ingredients in a stainless-steel beaker and immerse them in a liquid (water, stock, syrup, or oil), then freeze the mixture solid at a temperature of −22 to −20 °C / −8 to −4 °F. The beaker then goes into the Pacojet, where the system's high-speed blade starts to mill down the hard, frozen food mass at around 2,000 rpm.

As it grinds away, the machine also blows jets of air, pressurized to 1.7 bar / 25 psi, at the food. The jets supplement the shearing forces of the cutting blade with a shattering effect. This dual-grinding process, **pacotizing**, yields food particles as small as two microns (80 millionths of an inch) across.

Pacotizing typically warms the frozen sample by 7–10 °C / 13–18 °F, so that after processing, the food is typically between −15 °C and −12 °C / 5 °F and 10 °F. The combination of frictional warming from the grinding process and pressurized jets of air (which enters the machine at room temperature) causes the heat to rise. The exact degree of heating depends on the nature of the food matter: a fibrous fruit such as a mango will reach a higher postprocessing temperature than will a pear, whose flesh has less fiber against which the blade will generate friction.

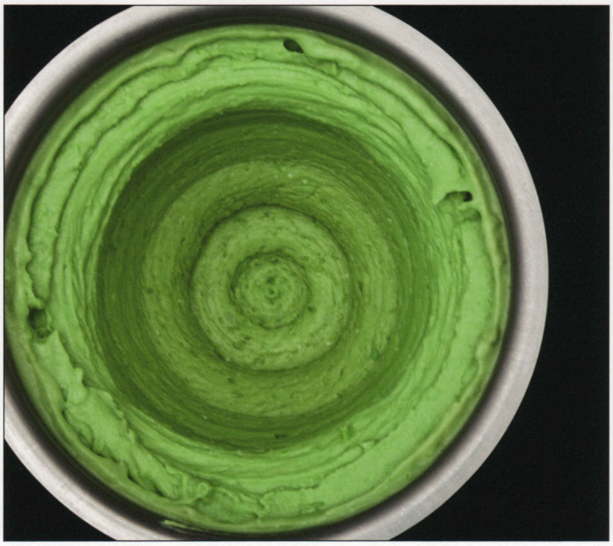
The texture of the final product ranges from a fine, dry frozen powder to a smooth, ice cream-like consistency—it all depends on the freezing point of the mixture, the amount of solids (such as salt or sugar) and liquids (such as alcohol) dissolved in it, and the size of the ice crystals when the grinding is done. Fortunately, you have some control over these variables.

You can lower the freezing point of most solutions by adding soluble solids or liquids, thus exploiting a chemical effect called **freezing-point depression.** If you don't depress the freezing point, you will end up with a dry, frozen powder rather than an ice cream. That may be exactly what you're after. Some Modernist chefs have had great success freeze-grinding savory foods into this unusual form. For example, they can prepare a vegetable, spice, or seasoning blend, then process it in a Pacojet to make a fresh, finely ground puree. This form is ideal for incorporation in a sauce, a soup, or another dish.

You may also serve the powder directly, an

Some mixtures are best pacotized twice. To start another run, you press the start button a second time and stand ready to hit the stop button immediately after the blade contacts the frozen mix, which is indicated by the portion light bar. Refreezing between the first and second passes, although time-consuming, yields even smoother results.

The Pacojet can process a vegetable to make a smooth texture like that of ice cream or a fresh, finely ground puree powder for adding to a sauce or soup.



THE HISTORY OF

The Pacojet

Wilhelm Maurere, the Swiss-born engineer who invented the Pacojet while living in Brazil in the 1980s, reportedly built a prototype that incorporated a handheld electric drill. His patent was later acquired by a group of private investors from Switzerland, who established the product's manufacturer, Pacojet AG. Maurere had originally intended to build a soft-serve ice-cream machine for home use, but high manufacturing costs made the device too expensive for the home market. So it was repositioned for professional cooks.

Soon after the Pacojet was introduced in 1993 in Europe, it found its way into many professional kitchens. Those who tried it found it invaluable for making ice cream and sorbet. Over time, chefs developed certain savory applications for the machine, but it is fair to say that most Pacojets are still used for preparing pastry and dessert dishes.

The first Pacojet imported into the United States was used by the master chef Gray Kunz at the famed New York restaurant Lespinasse. One of us (Myhrvold) saw it there in 1995 and, after becoming intrigued, purchased what was then just the second Pacojet in the United States. At that time, the product had not yet received Underwriters Laboratories' safety approval (required for all electrical appliances in the U.S.), so strictly speaking, it was illegal. But the Pacojet worked well, and by the next year, UL approval was in the works, and test-marketing had begun.

approach pioneered by Ferran Adrià. The frozen granules that come from a Pacojet can be quite tasty; they melt instantly in your mouth. Outstanding examples of Pacojet-enabled dishes include a novel powdered-cheese course (see page 411) and a knockout powdered steak tartare (see page 3·62).

If, however, the freezing point of the mixture is lowered enough and the percentage of soluble solids is high enough, the result of grinding will be a smooth texture like that of ice cream or sorbet. Although some added fat and soluble solids are usually necessary, the amounts you add should be lower than in conventional ice-cream churning to produce the best results.

Unlike conventional ice-cream production, Pacojets don't whip air into the fat. So they produce a denser product that melts more quickly than churned ice cream. Pacotized food typically expands during processing only by about 25%–35% in volume, whereas churned ice creams typically expand more—one source of their softer, slower-melting texture.

Pacotizing is also different from ice-cream churning in the way it makes ice crystals. The Pacojet creates small ice crystals by grinding up large ice crystals rather than by growing them small, which is the usual goal when making ice cream.

Experienced Pacojet hands find that a blast chiller (see page 255) provides the ideal way to freeze the material that is to be used in a Pacojet because it can freeze samples to the desired temperature very quickly. Conventional freezers are better suited to storing the end product.

You might find it tempting to use liquid nitrogen to freeze the Pacojet beakers even more quickly than a blast chiller can. We have tried this and found that it does work, as long as you place the beakers in a freezer for a while to warm them after their dip in the nitrogen. Try to pacotize a mixture that is too cold, and you risk breaking the blade. It is very important that no liquid nitrogen enters the beaker; frictional heating during pacotizing will boil the nitrogen and create excess pressure in the Pacojet chamber, possibly causing it to explode. A similar problem can occur if a carbonated liquid gets into a beaker prior to processing.

Regular Pacojet users find it convenient that the pacotizing chamber is clearly demarcated in units of about a tenth of a beaker, or 100 ml / 3.5 oz of volume for each tick mark. This volume scale makes it easy for a cook to process a single 100 ml / 3.5 oz serving to order and to then return the remainder to the freezer, where the beaker's contents can remain safely frozen for months. Each serving unit typically weighs about 100 g, and its final volume ranges from 125–135 ml / 4.2–4.6 oz after it expands. The first serving unit

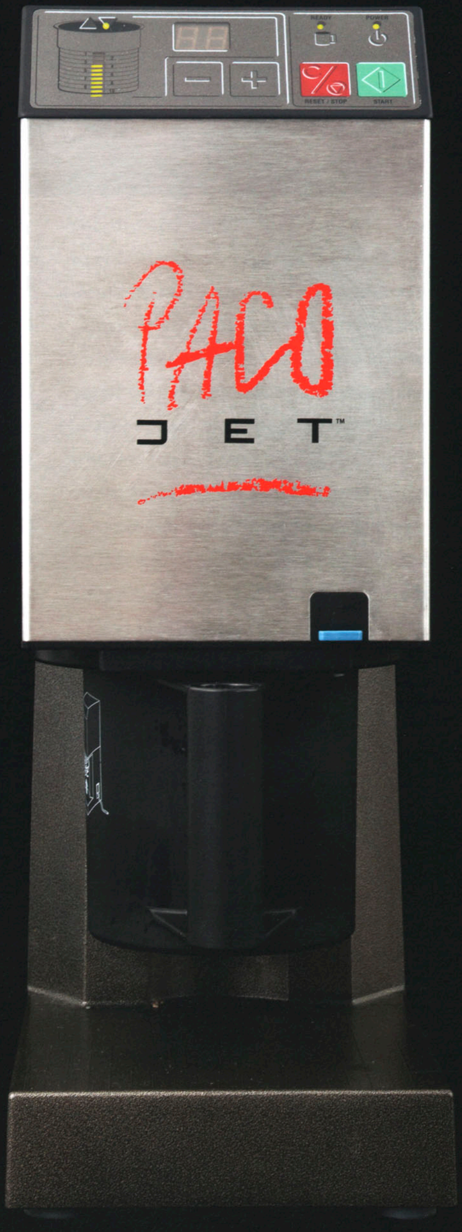
The Pacojet is dry-grinding when it produces a powder, but one can argue that it is doing partial wet-grinding when it creates a sorbet or ice cream-like texture in a food, and that it is doing full wet-grinding when the Coupe-Set blades are operating.

SORBET (OR POWDER) IN A FLASH

Want instant, silky-smooth ice cream or sorbet? The Pacojet was designed precisely for this purpose, but versatility of this countertop device is such that it has become relatively common in restaurants and hotel kitchens worldwide. The machine uses a sharp, tough blade that spins at high speed to mill, or progressively grind, a solid block of ice into a smooth paste. Besides producing frozen desserts, this unusual process can be effective for pureeing savory items or making concentrates for soups or sauces.

Before using the Pacojet, you place the food into a special steel beaker that you've usually topped up with liquid (juice, cream, or water). You then freeze it solid at about −22 °C / −8 °F; otherwise, the blade won't process it properly.

Pacojet ice cream and sorbet is exceptionally smooth because the machine grinds ice crystals to a very small size. When applied to foods that contain little fat or sugar, the machine will produce a frozen powder that may be served directly or warmed and used as a puree or an ingredient in a sauce or soup.

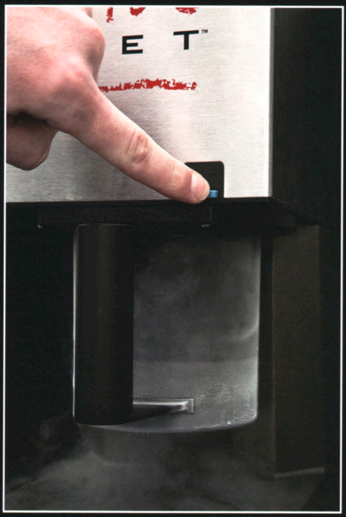


The Pacojet machine mills frozen food into a fine, icy paste or powder.

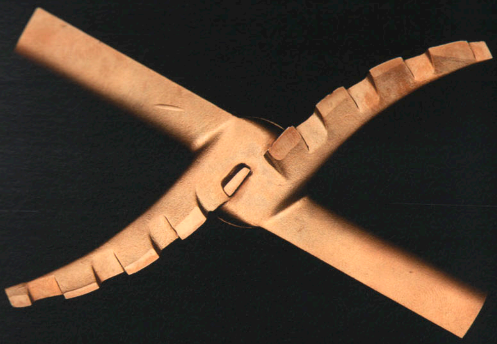
The portion light bars illuminate to show the progress of the process. The first bar comes on when the blade makes contact with the top of the frozen mix. That is also when you hear the motor working harder.

The stop button halts the pacotizing process when you push it and returns the blade to the top of the beaker.

Digital controls allow the user to set the Pacojet to process a whole beaker, or you can direct it to process food in units of about 100 mL / 3.5 oz of material (about 10% of a beaker's volume). The remainder can be left in the beaker and stored in a freezer for later use.



The air-release button enables users to reduce air pressures in the beaker before removing it after processing. Pressures during pacotizing reach 1.2 bar / 17 psi and must be bled off safely. In cases in which incorporating air into the product is problematic, you can hold down the button while pacotizing.



The pacotizing blade progressively mills a solid block of ice down to the consistency of paste or mousse. It also whips air into the resulting frozen slurry mixture.

Each stainless-steel beaker holds a maximum of 1 l / 1 qt of food. In practice, this means 700–800 g / 25–28 oz, depending on the amount the sample expands during freezing.

The spray guard assembly (not shown) keeps food inside the machine.

The protective outer beaker features a handle to permit cooks to carry it around the kitchen. It serves to lock the beaker in place.

The base food material, whether it is sweet or savory, must be frozen solid before milling is attempted.

to be pacotized in a beaker may contain a bit more or less than the standard serving unit, because the top of the frozen material is usually not completely level.

This single-serving feature is especially useful for busy cooks. A chef who uses a Pacojet invariably winds up with a freezer full of beakers containing various flavors and ingredients ready to be pacotized when needed. When the chef selects one of them for processing, the machine sends its mobile blade down into the beaker until the blade just contacts the top of the frozen mix; this measurement allows it to determine exactly how much farther it must mill down into the icy mass to pacotize a 100 ml / 3.5 oz portion.

The Pacojet processes that portion in 20 seconds. To pacotize smaller quantities, just count off the seconds and press the red stop button. For example, to process 25 ml / 0.8 oz, hit the stop button after five seconds.

The countdown starts when the blade contacts the frozen mixture. You can either do this by ear (the grinding noise will tell you) or wait until the green light bar starts to flash.

The Pacojet has an accessory called the Coupe-Set that contains blades for grinding or pureeing nonfrozen food—even a blade for whipping foams such as whipped cream or egg whites. The main value of the Coupe-Set is in space-limited kitchens, where it can save the counter space that another, less-flexible machine would take up. The Pacojet suffers somewhat because its beakers are opaque, which doesn't allow you to watch the processing proceed as you can with most mixers or food processors.

For more on how the freezing point of a liquid is affected by other substances dissolved in it, see Freezing and Melting, page 1·304.

Ice cream base is typically a high-fat-content emulsion. The particular fats that are incorporated affect the texture of the final product. Unsaturated fats, including olive oil and most other vegetable oils, tend to freeze at a lower temperature than do saturated fats such as cocoa butter, milk fat, butter, or lard.

Liquid nitrogen temperatures also affect texture; the colder the mix, the more likely the Pacojet will turn it to powder.

EXAMPLE RECIPE

PACOJET PEA SOUP

Yields 660 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Green peas, frozen	300 g	100%	① Combine and transfer to Pacojet beaker.
Heavy cream	200 g	67%	② Freeze to at least −20 °C / −4 °F.
Pea juice see page 336 (or white vegetable stock)	150 g (from 500 g of peas)	50%	③ Pacotize once. ④ Optionally, freeze and Pacotize once more for smoother texture. ⑤ Transfer soup to pot, and warm until just melted and velvety.
Salt	6 g	2%	⑥ Season.
Mint leaves, fine julienne	3 g	1%	

(1996)

This soup is best served when at or below 60 °C / 140 °F, so that it retains its sweetness. At higher temperatures, the peas will taste cooked and less sweet.

EXAMPLE RECIPE

MOZZARELLA POWDER

Yields 450 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Buffalo mozzarella	250 g	100%	① Cut into 2.5 cm / 1 in cubes.
Buffalo mozzarella brine	100 g	40%	② Dissolve glucose into whey.
Glucose syrup DE 40	100 g	40%	③ Blend whey mixture with mozzarella cubes until smooth.
			④ Transfer mixture to Pacojet beaker and freeze to at least −20 °C / −4 °F.
			⑤ Pacotize once without venting.
			⑥ Serve powder immediately, or store frozen for up to 1 h.

(2010)

EXAMPLE RECIPE

FROZEN CHEDDAR-CHEESE POWDER

Yields 400 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Water, cold	250 g	100%	① Combine.
Agar	2 g	0.8%	② Bring to a boil, and hold for 1 min to fully hydrate.
			③ Blend over ice-water bath to create fluid gel.
Sodium citrate	8 g	3.2%	④ Disperse into fluid gel.
			⑤ Bring mixture to a simmer.
Cheddar cheese, finely grated	150 g	60%	⑥ Incorporate slowly into simmering mixture until fully melted.
Salt	2.5 g	1%	⑦ Transfer mixture to Pacojet beaker, and freeze to −30 °C / −22 °F.
			⑧ Pacotize once, and refreeze to −60 °C / −76 °F.
			⑨ Pacotize again once more to make a very fine powder.
			⑩ Serve immediately or store frozen for up to 1 h.

(2010)

EXAMPLE RECIPE

FROZEN CRÈME-FRAICHE AND PINE-NUT CREAM

Yields 1 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Water	500 g	500%	① Blend together.
Glucose syrup DE 40	135 g	135%	② Place in Pacojet beaker, and freeze to at least −20 °C / −4 °F.
Crème fraiche	100 g	100%	③ Pacotize once.
Pine-nut butter see page 418	100 g	100%	④ Serve frozen cream immediately, or freeze.
Skim milk powder	79 g	79%	
Isomalt	60 g	60%	
Salt	10 g	10%	
Sugar	10 g	10%	
Guar gum	2 g	2%	

(2009)

Wet-Grinding

Wet-grinding occurs when you reduce the size of particles that are suspended in water or another liquid. Common examples of the results of wet-grinding in the kitchen are pureed meat or vegetables. The high water content of most plant and animal foods means that even if you start by dry-grinding, it pretty rapidly becomes wet-grinding as liquid is released. If you grind peanuts or tree nuts, something similar happens, but instead of water, the released liquid is oil. Another example of a product of wet-grinding in the kitchen is an emulsion. Indeed, wet-grinding is far more common than dry-grinding and ranks as one of the most important food preparation tasks.

Wet-grinding is, in general, more effective at particle reduction than dry-grinding because shear forces transmitted through the suspending liquid can be an effective way to break up particles.

A wide variety of wet-grinding tools are used in conventional kitchens. Blenders and food processors are the most familiar examples. Each has rotating blades that cut the food directly, which is important in the coarsest phase of grinding. When the particles become small, hydrodynamic forces that the blades induce in the liquid become an important way to disrupt the food particles.

The very different designs in kitchen wet grinders reflect their differing tasks. A food processor handles dry, soft food better than a blender does. The food processor sits somewhere between dry-milling and wet-milling; it is thus, in many ways, the most versatile of grinding tools. A typical processor design features a wide blade that sweeps over a broad surface very close to the flat bottom. Food has nowhere to hide, so it gets cut and flung violently against the container walls.

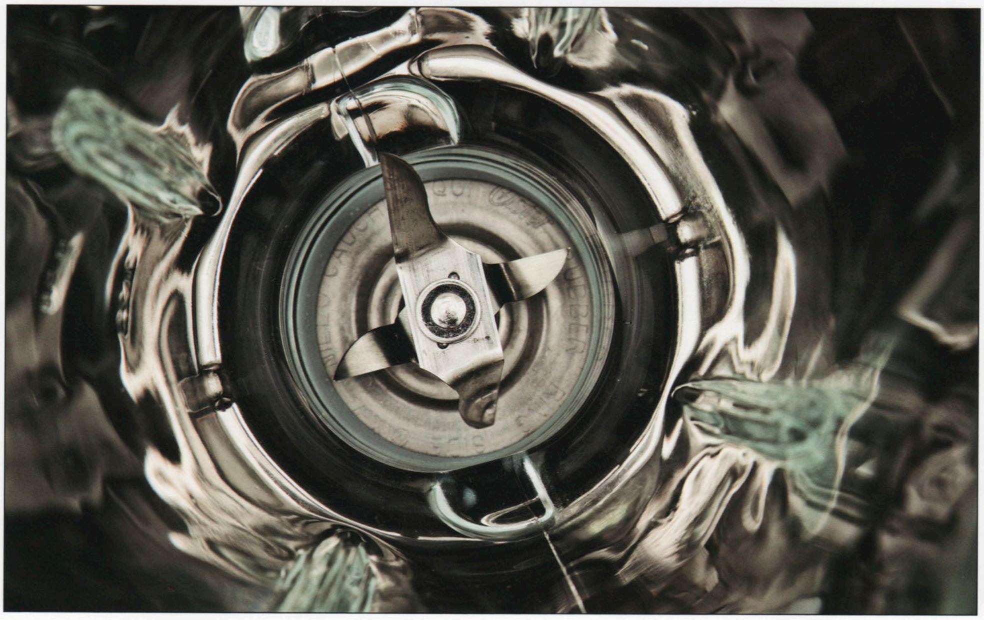
Blenders are more purely oriented toward wet-grinding. They rely on the liquid being thin enough that it can flow past the blade area, which is usually quite narrow compared with the wide, flat bottom of a food processor. As a result, very thick liquids may not receive adequate turnover. Large chunks of food can get stuck or be blocked from the blade area. Food processors are better for those tasks. Alternatively, if a liquid is too thick for a blender, dilution with a little added water (or oil) usually improves the situation.

The design choices that make a blender problematic with some foods is a real benefit with others. Hydrodynamic forces generated in the liquid as it flows through the narrow passage and past the blades subject food particles to shear forces that can literally rip them apart. Blenders have motors that spin at higher speeds than food processors do to accentuate this effect.

The combination of speed and shear makes blenders better at wet-grinding and enables them to produce smaller particles and smoother purees than a food processor can. As a result, household

The food processor was invented in the late 1950s by Pierre Verdun, a French catering company salesman. In 1960, the company Robot-Coupe was formed in France to sell food processors as a product and became very successful.

In 1973, Carl Sontheimer licensed the technology from Robot-Coupe and offered it for sale in the US under the brand name Cuisinart. The Massachusetts Institute of Technology now awards the Carl G. Sontheimer Prize for Excellence in Innovation and Creativity in Design in his honor.



Conventional hand blenders or upright blenders are the primary tools used for wet-grinding tasks. Their high-speed blades generate tremendous shear forces, which are proportional in strength to the speed of the blade and the gap between the blade and the surrounding container. As a result, blenders tend to be fairly narrow in the region near the blade. This design works well for liquids but can be a liability if large chunks of food get stuck.

blenders and their higher-powered commercial cousins such as the Vita-Prep are excellent tools for many wet-grinding tasks.

Upright blenders are the most common, but immersion blenders, also called handheld blenders, are quite similar. Instead of sitting at the bottom of a narrow canister, the blades reside in a housing on the end of a shaft. This design allows them to be immersed from the top into a bowl or pot. Immersion blenders are inexpensive and are useful for many small tasks. However, their limited motor power and small blades make them inferior to upright blenders for most serious wet-grinding tasks.

Unfortunately, blenders (whether upright or handheld) have an intrinsic limitation: they are generally unable to make particles smaller than 10–12 microns / 0.0004–0.0005 in, and even that is not easy to achieve. This dimension is just above the range of sizes that the human mouth can detect as a particle. As a result, a blender is not able to create the very smoothest purees or the finest emulsions. A puree or cream soup may be noticeably gritty if a blender is used to wet-grind it. Fortunately, other tools can reduce size further.

Big Iron for Blending

A **rotor-stator homogenizer** looks a bit like a milk shake mixer (see Better than a Blender, page 420). The motor sits on a vertical stand and drives a specialized blade assembly called the generator, or rotor-stator, that sits at the end of a shaft.

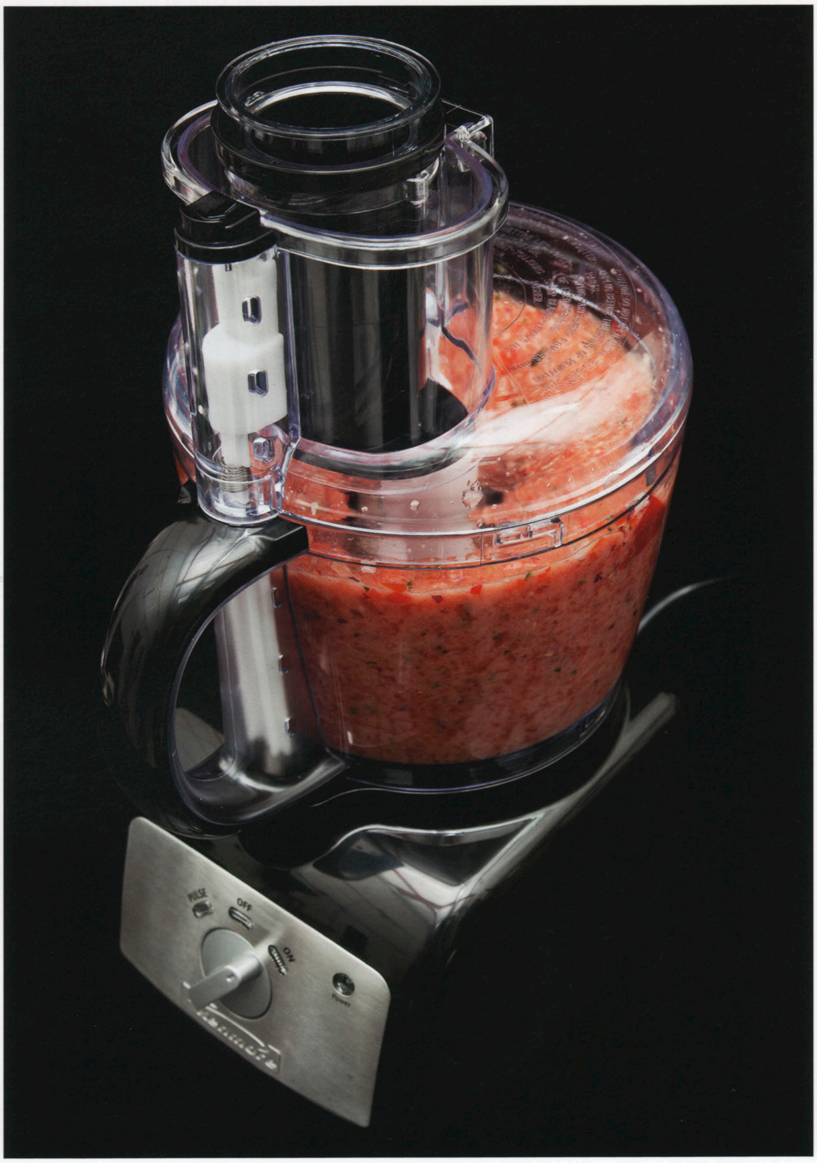
The blade, or generator assembly, has two parts called—unsurprisingly—the rotor and the stator. You may have heard these terms used to describe the central parts of an electric motor, and the analogous parts of the homogenizer blade are similar in their arrangement.

The **rotor** spins fast—up to 20,000 rpm—on its axle inside a closely matching, precision-built **stator**, which remains stationary (hence the name). The clearance between the two can be as tight as 25 microns / 0.001 in. The motion of the rotor forces the liquid through the tiny gap in the assembly, which creates tremendous hydraulic sheer forces that rip apart any particles suspended in it. The violence of the process is such that solid particles break up into even finer bits, and colloidal globules emulsify further into the liquid.

Rotor-stator homogenizers are more flexible in their capacity. They range in size from small units with very thin generators meant to process a teaspoon or less of material in a test tube to large units that can process tens of liters at a time.

Colloid mills are next along the technological path toward smaller particle sizes. These mills work on dry ingredients, thick pastes, and even pourable emulsions such as salad dressings. They have the advantage that nothing can get past the grinding parts, which work essentially like a rotor-stator homogenizer on steroids. The rotor-stator blade assemblies in a colloid mill are much larger than those in a homogenizer and typically

Unlike a blender, a food processor excels at certain wet-grinding tasks because its large blade enables it to cut big pieces without jamming.



feature multiple rows of teeth and adjustable gaps that allow the tool to handle very hard and large pieces of food, such as whole nuts. Multiple passes at successively smaller gap sizes can grind food into fine pastes or butters. The design forces all of the material through the rotor and the stator. In contrast, a rotor-stator homogenizer is immersed in the liquid and relies on fluid flow to mix things adequately. As a result, some parts of the liquid might not pass through the generator. This omission can't happen with a colloid mill. Because a colloid mill generates considerable heat, most models include a water-chilled jacket.

Colloid mills are generally sized for large-volume operations that process liters of liquid. You pour the food through the colloid mill. If necessary, it can be poured through again in another pass to get a finer result. The maximum amount of food the machine can handle depends on the model, but it can be substantial.

The Thermomix is a high-quality blender combined with a heating element into an all-in-one tool for wet-grinding and heating. It is therefore very useful. It would be even more useful if the temperature control on the heating element were more accurate.

The **high-pressure homogenizer** takes another step toward even tinier food particles. This is our preferred tool for making supersmooth sauces, creams, purees, and emulsions.

There are several kinds of high-pressure homogenizers. Some shoot jets of compressed air or nitrogen (at pressures of up to hundreds of bars or thousands of psi) at a stream of liquid that is forced (also at high pressure) through a small orifice. Others shoot high-velocity jets of food at an impact plate or blade, where the entrained food particles are smashed to smithereens. Still others use pulsating jets of high-pressure air that alternately compress and decompress the stream of food. Upon decompression, the liquid is literally torn apart into voids that implode. This process, called **cavitation**, puts food particles under high stresses and rips them apart.

High-pressure homogenizers use high-speed, high-friction techniques that produce considerable heat. This can cook or even ruin the food. These devices thus almost always require cooling.

High-intensity sound carries enough power to homogenize food by using the process of cavitation. An **ultrasonic homogenizer** generates high-intensity, high-frequency sound and passes it through a precision-machined, solid titanium cylinder called the **horn**. The horn is immersed in the liquid to be homogenized. Vibrations in the cylinder create sound waves in the water of such high intensity that they cause cavitation bubbles to form, putting enormous strains on any surrounding food particles. Although this microscopic cavitation effect takes more time, with a bit of patience, Modernist cooks can create ultra-emulsified liquids with suspended droplet sizes no bigger than a micron or two.

Traveling further into the realm of the small is to enter the unexplored nanoparticle scale, which can behave in ways that differ from larger-scale particles that are composed of the same substance. Who knows? Pioneering chefs may someday uncover now-unimagined ways to exploit nanotechnology to make sauces or drinks that change color as they cool, or when you stir them or view them from different angles. Perhaps we might even see a dish that releases, like Willie Wonka's fictional chewing gum, a preset sequence of flavors as you eat it.

BUBBLY BREAKDOWN

Want the state-of-the-art in handheld food processing? Try an ultrasonic homogenizer. This handy device generates ultrasonic vibrations to break down liquids, producing very fine emulsions and purees. It works by creating large numbers of cavitation bubbles that create minute shock waves as they pop, which rips apart solid particles or oil droplets that are suspended in the liquid. An ultrasonic homogenizer works well on thinner liquids but less so with thick liquids. Although the ultrasonic homogenizer's capacity is somewhat limited, it is much cheaper than a typical high-pressure homogenizer yet can produce comparable particle sizes if given enough time.

Stir the liquid as you run the device; otherwise, the bubbles emanating from the vibrating tip will be distributed unevenly, which will make the resulting product less uniform.

The control unit lets you set the power level and timing of the process.

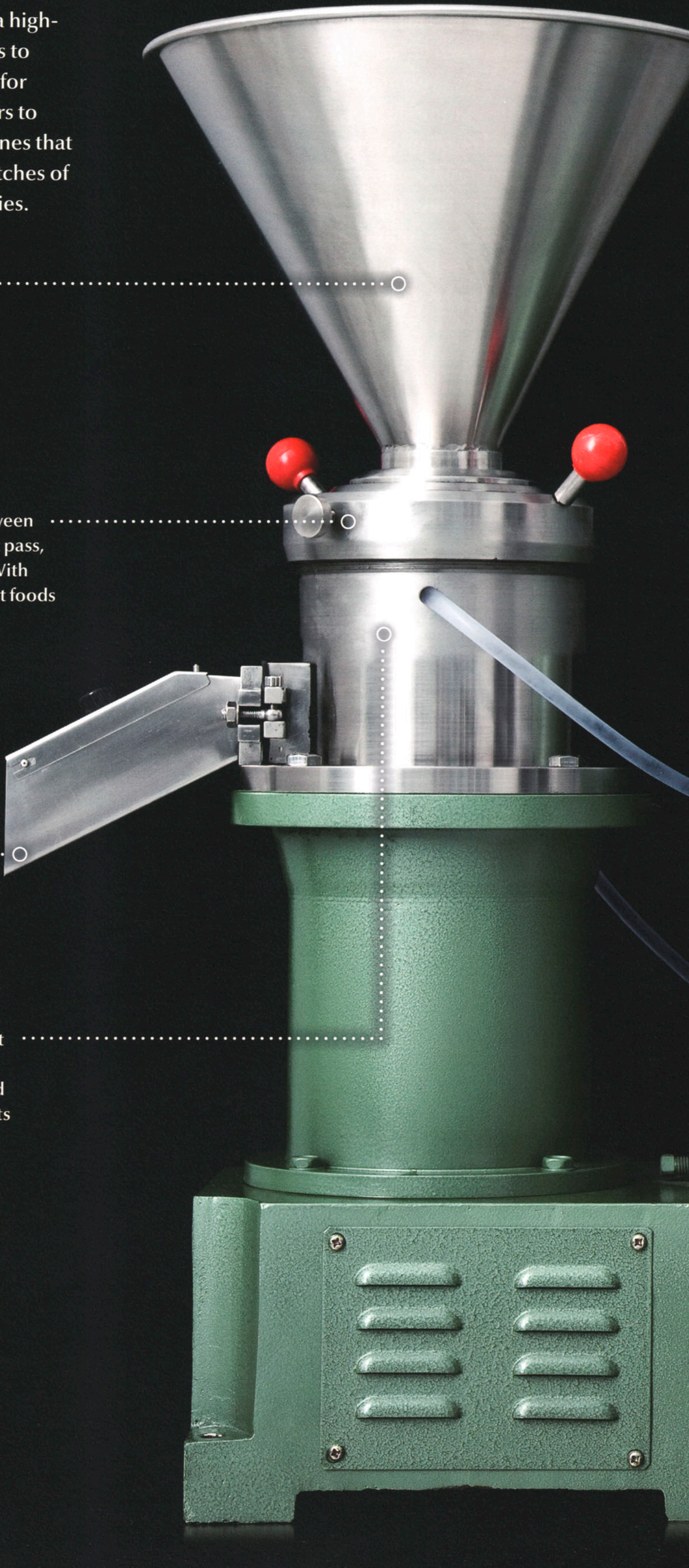
High-frequency vibrations of the tool tip—faster than 20,000 times a second—cause the water to cavitate. This phenomenon, which resembles boiling water, causes the pressure in the fluid to fall below its vapor pressure in spots, which produces tiny bubbles. As these cavitation bubbles implode, they produce very high shear forces that rip apart the solid particles or oil droplets in liquids.

The broad-tipped horn (shown here) is better for homogenizing a large volume of liquid, but it generates weaker cavitation forces. A sharper-tipped horn is better for processing a small volume; it produces much stronger cavitation forces but in a small amount of liquid.

The homogenization process can draw 200–750 W of power, enough to heat liquids and alter their flavor, so a cook may need to cool the liquid on ice. Monitor the temperature to guard against overheating.

BUMP AND GRIND

Sometimes a chef needs something that's heavier-duty than a conventional blender or homogenizer. A colloid mill is a high-volume device that grinds food and other fluid materials to a smooth and uniform consistency. The machine works for processing everything from dairy products to nut butters to vegetable purees. Colloid mills vary in size from small ones that fit on a counter to enormous units that process huge batches of matter for the food, textile, and pharmaceutical industries.



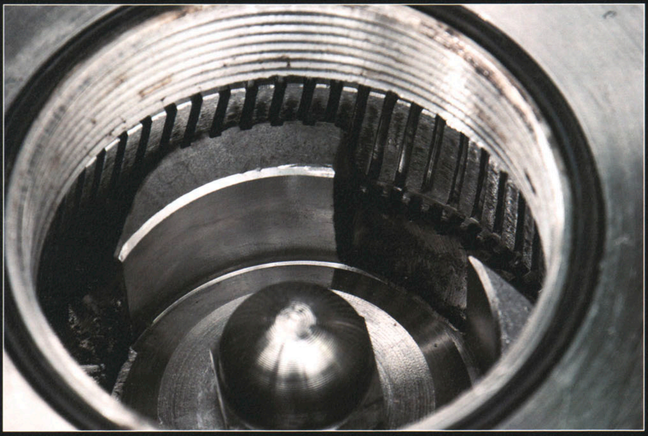
The hopper feeds the input material into the mill. Some colloid mills will take solid pieces of food, such as peanuts or nuts, but other models require users to prepare the feedstock by grinding it into a liquid slurry or pourable paste.

An adjustable collar allows you to adjust the size of the gap between the rotor and the stator. Typically you set the gap wider for a first pass, then tighten it for subsequent passes to produce a finer puree. With enough passes, a colloid mill can usually grind even the toughest foods into particles of two microns or smaller.

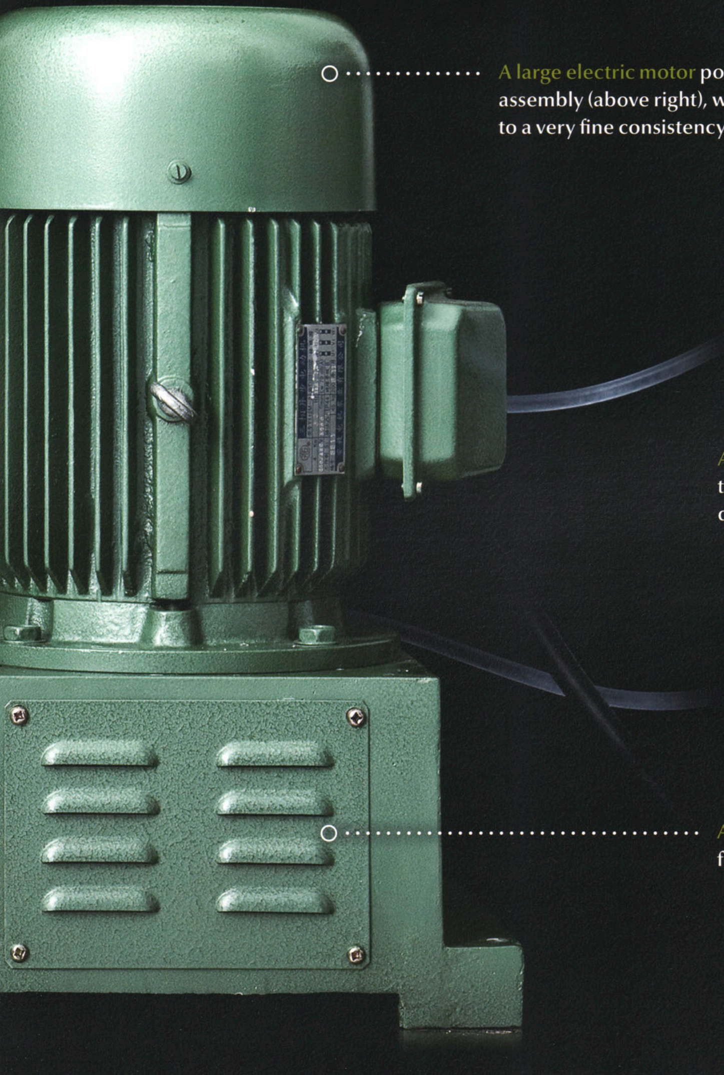
A chute carries the processed food out of the machine.

A water jacket cools the rotor-stator compartment that it encloses with cold water pumped from a chilled water bath. Cooling helps prevent the food from overheating as it is processed. It also prevents the rapidly spinning metal parts from heating, expanding, colliding, and self-destructing.

The hopper mouth typically incorporates a screw-feed mechanism that will force even a thick, viscous paste such as peanut butter into the mill.



The rotor-stator assembly is the business end of the colloid mill. This part of the tool resembles a similar device on a rotor-stator homogenizer, except that the mill forces all the material through the rotor-stator without requiring the cook to stir it. The device applies a powerful combination of shearing, grinding, and high-speed mixing forces to reduce the size of the particles in the fluid.



A large electric motor powers the rotor-stator assembly (above right), which reduces the food to a very fine consistency.

A chilling water bath (not shown) keeps the temperature of the food from rising too high during milling.

A drive belt inside the casing transfers power from the motor to the rotor mechanism.

HOW TO Mill a Creamy Nut Butter

Peanut butter is a staple of pantries and lunch boxes, yet smooth nut butters are difficult to create at home. When using most blenders and food processors, the oil will separate before the nuts are ground fine enough to form a creamy emulsion. Creating a pleasingly smooth nut butter requires a colloid mill.

1 **Place the nuts in the feed funnel of the mill.** Pistachios are shown below, but any other tree nut or peanuts will also work.

2 **Run nuts through the machine.** Repeat as many times as necessary to achieve the desired texture, tightening the collar for each successive pass. In using our machine, we have found that four passes yields a silky-smooth butter.

1a

2a

2b

2c

EXAMPLE RECIPE

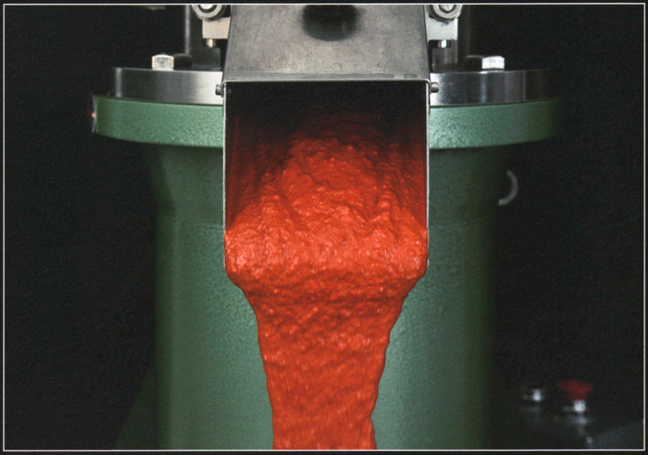
ROMESCO SAUCE

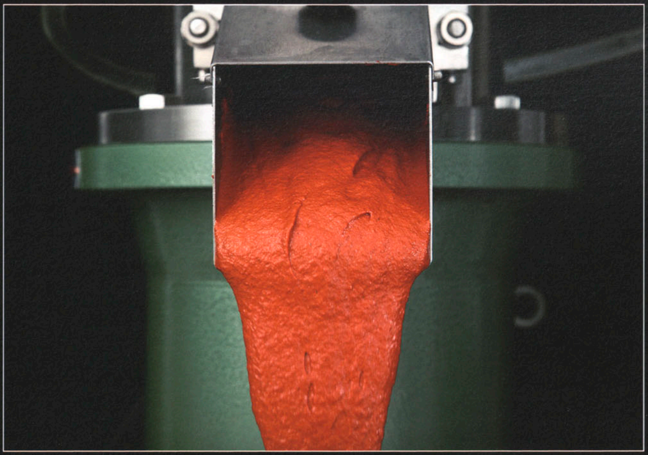
Yields 950 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Water	150 g	60%	① Soak peppers at room temperature for 2 h.
Smoked Hungarian paprika peppers, dried	20 g	8%	② Remove peppers from water, and blend into paste. ③ Press through fine sieve.
Olive oil	250 g	100%	④ Combine with paste.
Pine nuts, toasted	250 g	100%	⑤ Process mixture 3–4 times through colloid mill, using increasingly fine settings until desired texture is achieved.
Hazelnuts, peeled and toasted	150 g	60%	
Piquillo peppers (store-bought in jar, seeded)	150 g	60%	
Red wine vinegar	90 g	36%	
Garlic cloves, blanched	19.5 g	7.8%	
Paprika	9.5 g	3.8%	
Pomegranate molasses (store-bought)	8 g	3.2%	
Salt	to taste		⑥ Season.

(2009)


4


5a


5b


5c

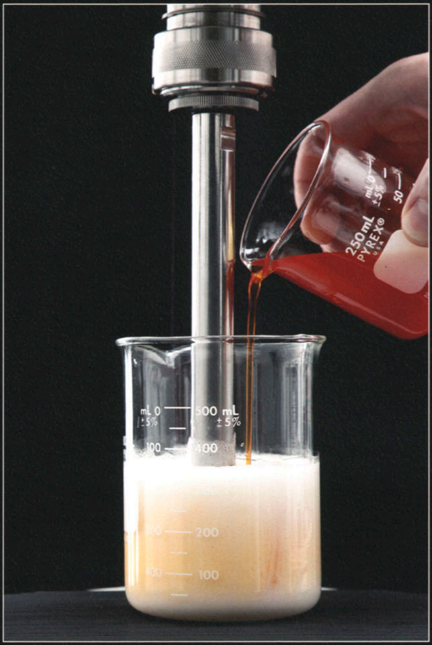
BETTER THAN A BLENDER

When the finest-textured puree or smoothest emulsion is the goal, a rotor-stator homogenizer is often the right tool for the job. The device resembles a conventional blender, with one key difference. In addition to a rotating blade, called a rotor, it also has a precision-built stationary structure, called a stator. The edge of the rotor spins extremely close to the matching edge of the stator, which forces the liquid through the thin gap between them. This action creates very high shear forces in the liquid—much greater than a blender can produce—so the rotor-stator homogenizer results in particles that are much smaller in size than a blender can make.

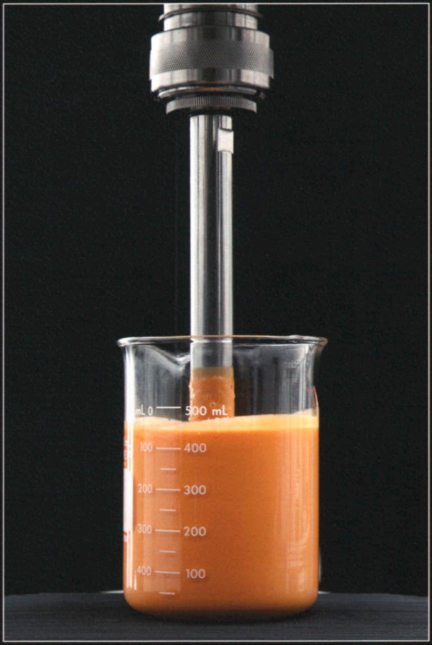
Be sure to disassemble the rotor-stator to clean it.

1 Select the rotor-stator needed to efficiently do the job. Choose a tip according to the size of your container. Larger tips will, in general, do a better job of breaking up soft chunks, but it is always best to start with a pourable puree or liquid. Attach the rotor-stator shaft or tip to the machine.

2 Place the mixture to be blended under the rotor-stator before turning it on. The tip should always be submerged before running.



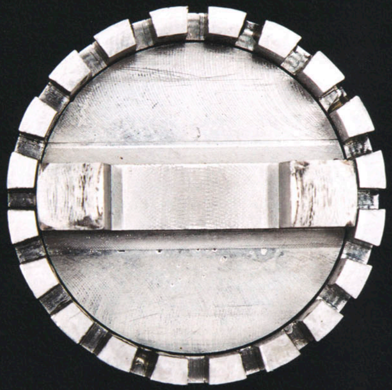
3 Puree or disperse the mixture. Start with a low speed—under 3,000 rpm—to prevent splashes and splattering. Gradually turn up the rpm until you can see the liquid smoothly flowing through the rotor-stator. Continue until you decide that the puree is smooth enough or that the ingredients are fully dispersed. Rarely, if ever, will it be necessary to crank the machine to the highest speed for culinary uses.



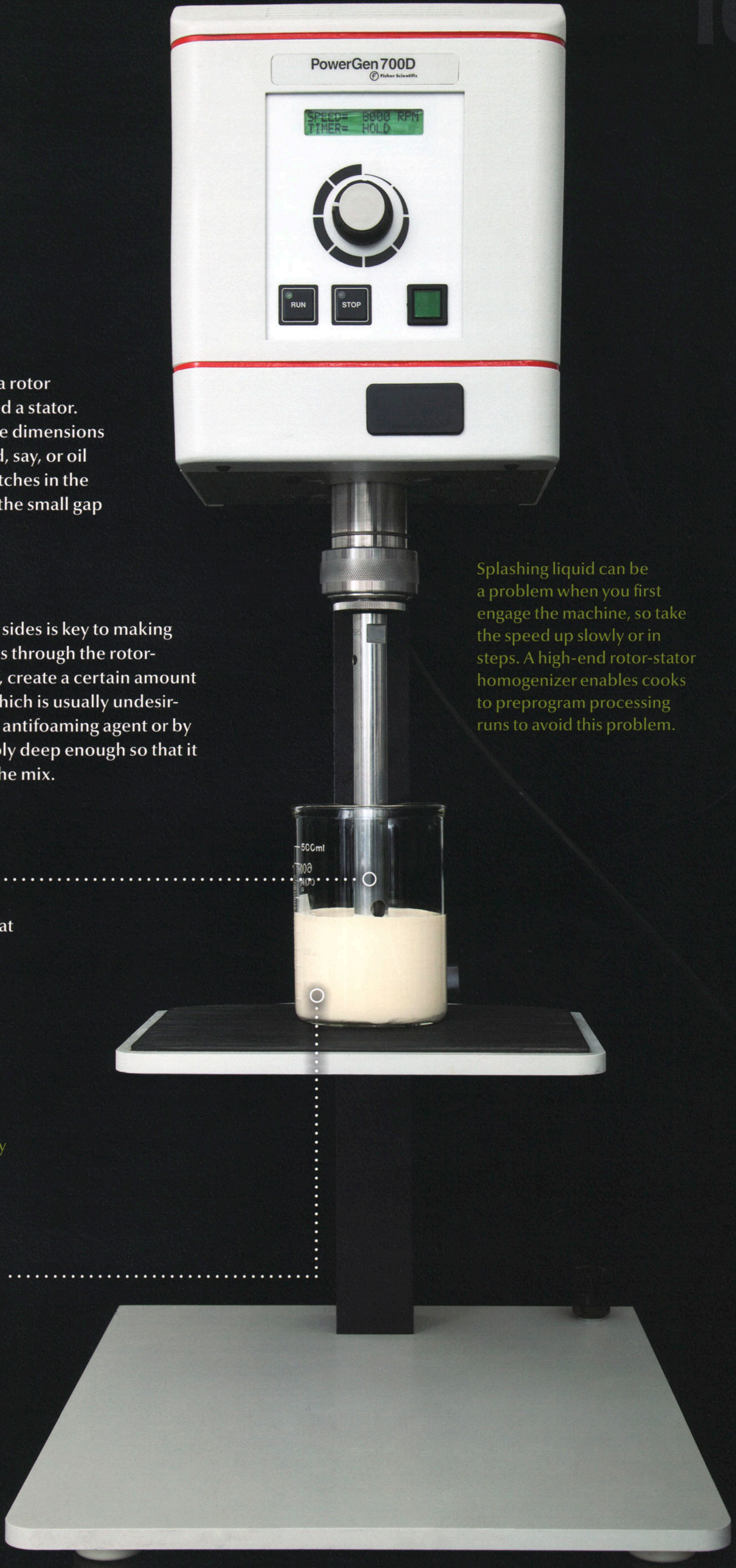
4 Ingredients can be added while the machine is running. If making an emulsion, gradually pour in the ingredient that needs to be dispersed and continue to homogenize it until it is completely incorporated.

As in any homogenizing method, the mechanical force of the rotor will heat the liquid, so operators must monitor the temperature of the food to avoid overheating.

Rotor-stator homogenizers also come in a small, handheld form, which can be useful for processing miniscule quantities of food—say, for grinding up pieces of truffle before adding them to a sauce. Cooks typically use a handheld unit with a test tube to hold the food matter because its depth helps prevent splashing.



The generator comprises a rapidly spinning blade, called a rotor (center piece above), and a notched stationary piece called a stator. Although the rotor is not sharpened, its design and precise dimensions allow it to strike, with great force, food particles in a liquid, say, or oil droplets in an emulsion. As it pushes the food through notches in the stator, high shear forces are imposed on food particles in the small gap between the rotor and stator.



Stirring the mix and scraping the sides is key to making sure that the food material passes through the rotor-stator, even though it does, itself, create a certain amount of suction. Formation of foam, which is usually undesirable, can be fought by adding an antifoaming agent or by inserting the rotor-stator assembly deep enough so that it can't incorporate much air into the mix.

Splashing liquid can be a problem when you first engage the machine, so take the speed up slowly or in steps. A high-end rotor-stator homogenizer enables cooks to preprogram processing runs to avoid this problem.

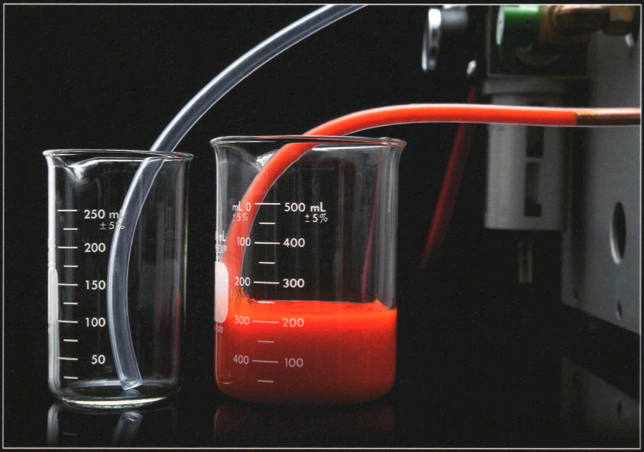
The stator is a stationary component that matches up precisely with the spinning rotor. The stator assembly typically features slots that draw in liquid after it has been severely sheared by the rotor.

Before milling, find out if the rotor-stator can accept larger food chunks. Some can, and some cannot. If not, you need to preprocess (puree) any chunky foods, such as vegetable matter in a blender or food processor.

The particle size that results depends on the size of the rotor-stator assembly and the rotation speed, but diameters below 10 microns (400 millionths of an inch) are typical.

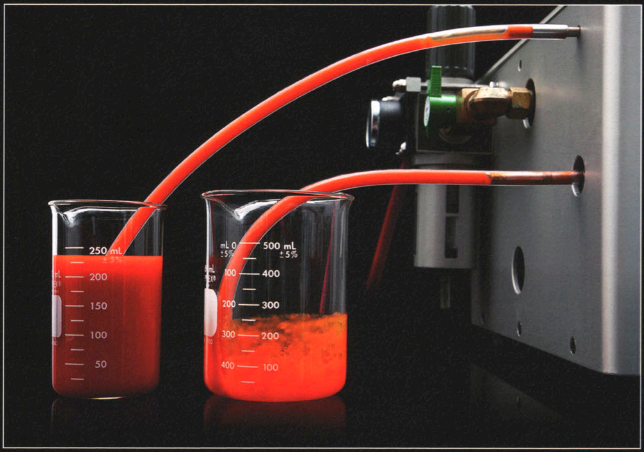
SMOOTH UNDER PRESSURE

An ultrahigh-pressure homogenizer is the premier method to reduce the size of particles in a puree or of droplets in an emulsion. The machine works by pumping a food liquid up to pressures around 2,000 bar / 30,000 psi, then slamming a jet of this high-pressure liquid against a solid metal surface called an impinger. This severe impact can reduce the particle or droplet size to below one micron (40 millionths of an inch), resulting in one of the smoothest, finest textures possible.



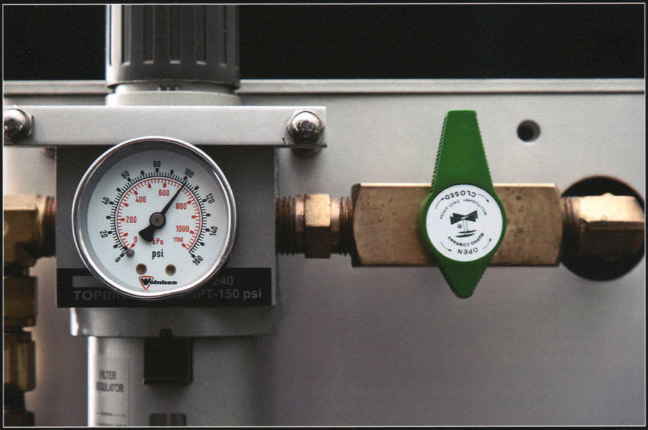
Preparation is key when using a high-pressure homogenizer; you should run the food material through a blender beforehand, if it isn't already a smooth liquid.

As its name proclaims, the homogenizer operates at high pressure. The exact pressure setting will depend on the model of the machine, the kind of food being processed, and how the machine has been adjusted for the run.

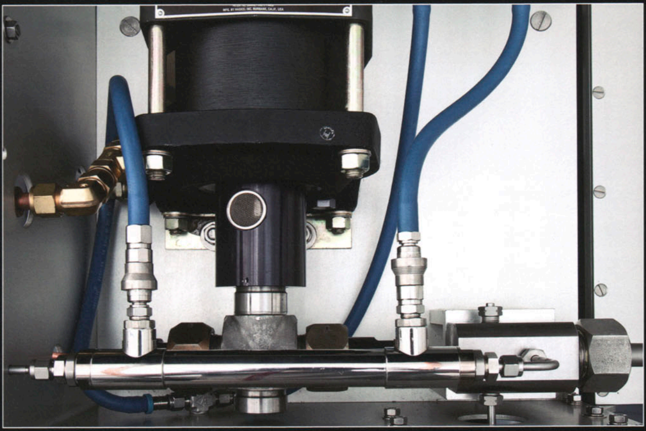


The homogenizer takes fluid from an input flask (at right, above), processes it, and sends the result to an output flask (at left). The machine simply sucks in thin liquids, but thick liquids and purees, ranging in consistency from mayonnaise to ketchup, will flow into the narrow inlet only if fed from a pressurized hopper.

A pass through the machine significantly reduces the size of the particle in the fluid. You can clearly see the marked difference in texture between the grainy material before (right) and the silky smooth liquid after (left) a single pass through the high-pressure homogenizer. Successive passes increase the uniformity of the particle sizes.



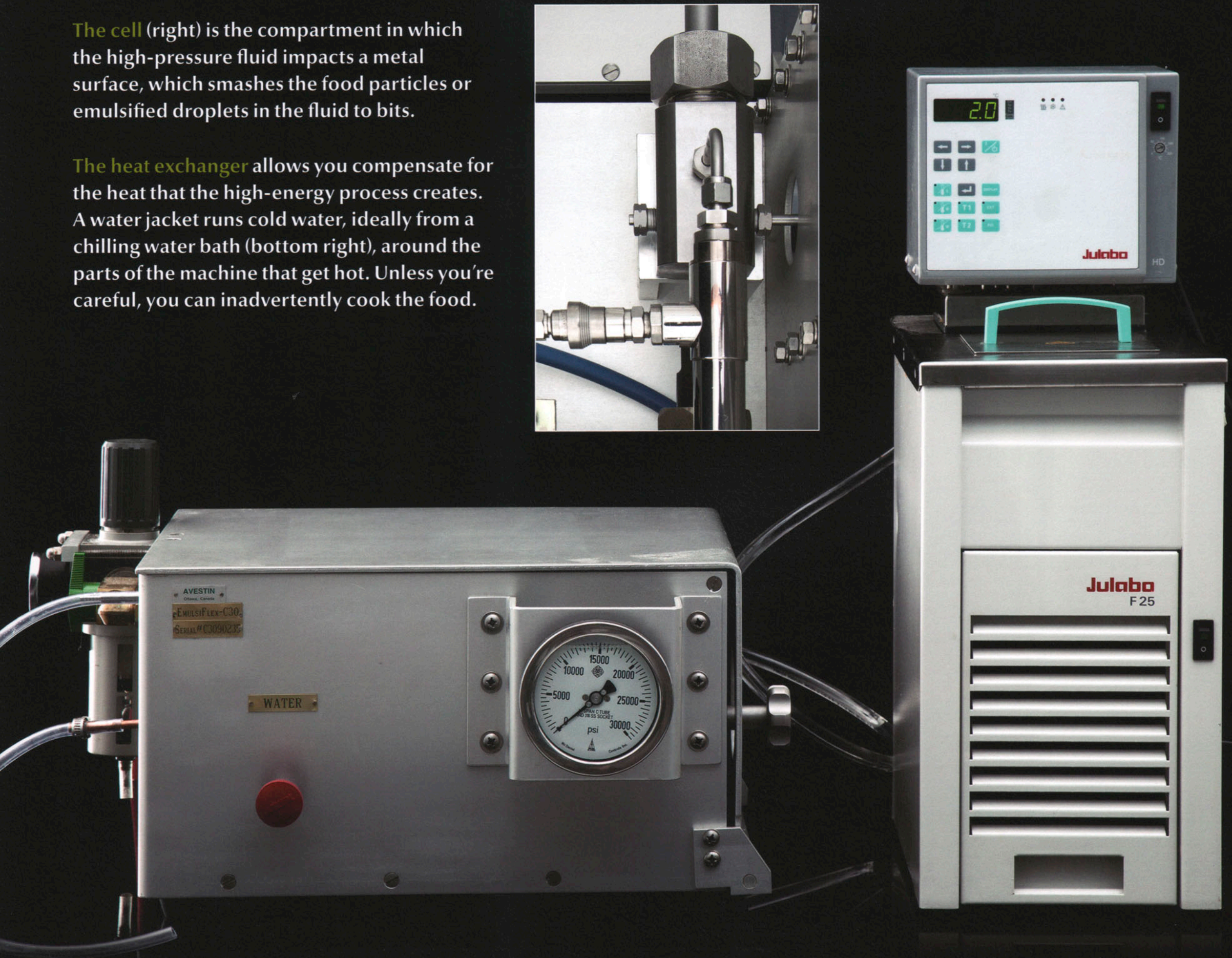
Compressed air provides the energy that drives most high-pressure homogenizers. The air comes from a machine-shop air compressor—the kind commonly used for spray-painting. Some homogenizers are electrically driven instead.



The pressure pump is one of the crucial elements of a high-pressure homogenizer. The design of the pump system and its valves allow the liquid to be moved around, pressurized, and then depressurized after processing it in the impinger.

The cell (right) is the compartment in which the high-pressure fluid impacts a metal surface, which smashes the food particles or emulsified droplets in the fluid to bits.

The heat exchanger allows you compensate for the heat that the high-energy process creates. A water jacket runs cold water, ideally from a chilling water bath (bottom right), around the parts of the machine that get hot. Unless you're careful, you can inadvertently cook the food.



PARAMETRIC RECIPE

FRUIT AND VEGETABLE PUREES

Vegetables have been mashed, pounded, whipped, and sieved—with varying degrees of success. A well-made vegetable puree is a sensual experience. You expect the bold, garden-fresh flavors to be as vibrant as they are silky and smooth.

Most cooks use a food processor, a household blender, or both to make purees. They work well enough, but sometimes their weak shearing force cannot achieve a smooth enough texture.

Commercial blenders are much more effective, thanks to their higher power. Blend in a little liquid, and with this tool you can quickly make purees from even tough ingredients, including corn, artichoke bottoms, and celery root.

If the ingredient is palatable after freezing, a Pacojet can do an even better job. Pacotized green peas, cream, and mint emerge from the beaker as a brilliant, fresh puree. You can also puree a food by using pressure to break down its particles.

MAKING A SMOOTH PUREE

1 **Prepare the vegetables by cutting into evenly shaped, small pieces, as indicated in the table below.**

2 **Combine vegetable with the liquid or seasoning indicated in the table. Set the weight of the produce to 100%. For example, use 12 g of butter for every 100 g of mushrooms.**

3 **Cook as indicated. Suggested methods, temperatures, and times are listed in the table.**

4 **Puree by using the tool indicated.** Optionally, process with rotor stator homogenizer, ultra high pressure homogenizer, or ultrasonic homogenizer for finer texture. For large quantities, a colloid mill is an ideal tool.

Best Bets for Vegetable and Fruit Purees

		Cook							
Ingredient	Prep	Method	(°C)	(°F)	(min)	Liquid	(scaling)*	Tool	See page
apple	peeled, quartered	sous vide	90	194	2½ h			commercial blender	5·17
asparagus	thinly sliced	sauté	high heat		10	vegetable stock unsalted butter	25% 15%	commercial blender	341
artichoke	hearts, thinly sliced	sous vide	80	176	45	vegetable stock olive oil	50% 5%	commercial blender	
beet	peeled, thinly sliced	sous vide	80	176	1 h	cooked beet juice unsalted butter	50% 15%	commercial blender	
broccoli	stems, peeled and sliced	sauté	medium heat		12	neutral oil	3%	commercial blender	426
	florets, sliced	boil	high heat		4	neutral oil	3%	Pacojet	
carrot	peeled, thinly sliced	sauté	medium-low heat		30	carrot juice carotene butter	50% 15%	commercial blender	3·301
cauliflower	florets, sliced	sauté	medium-low heat		1½ h	vegetable stock unsalted butter	50% 15%	commercial blender	5·281
corn	kernels	sous vide	85	185	1 h	corn juice unsalted butter	25% 15%	commercial blender	5·101
celery root	peeled, thinly sliced	sous vide	90	194	1½ h	skim milk unsalted butter	34% 15%	commercial blender	5·125
Jerusalem artichoke	thinly sliced	sauté	medium heat		45	whole milk unsalted butter	25% 15%	commercial blender	
mushroom	thinly sliced	sauté	medium-high heat		30	water unsalted butter	50% 12%	commercial blender	5·215
onion	peeled	oven roast	175	345	35	whole milk	12.5%	commercial blender	426
parsley	leaves	sous vide	90	194	7	water	to cover	Pacojet	
parsnip	peeled, thinly sliced	sous vide	90	194	45	unsalted butter	25%	commercial blender	
pea	whole	freeze and thaw		n/a		pea juice heavy cream	50% 10%	Pacojet	410
potato	peeled, thinly sliced	sous vide	100	212	35	unsalted butter heavy cream	50% 30%	food mill or ricer	3·296, 5·5
shallot	peeled, thinly sliced	sauté	medium heat		30	unsalted butter	25%	commercial blender	
spinach	leaves	blanch	90	194	7	water	15%	Pacojet	
winter squash	peeled, thinly sliced	sous vide	90	194	45			commercial blender	5·60

*(*set weight of prepared vegetable to 100%*)

EXAMPLE RECIPE

BROCCOLI AND HAZELNUT-OIL PUREE INSPIRED BY JACQUES MAXIMIN

Yields 400 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Broccoli florets	300 g	100%	① Blanch florets in 2% saline water for 3 min. ② Rinse in ice water.
Broccoli stalks, peeled and sliced	220 g	73%	③ Sauté stalks until golden and tender, about 4 min. Cool.
Neutral oil	10 g	3%	
Roasted hazelnut oil	30 g	10%	④ Combine with florets and stalks. ⑤ Puree in blender on high power until smooth. ⑥ Transfer puree to beaker. ⑦ Process with rotor-stator homogenizer at 4,000 rpm until extremely silky, about 3 min.
Salt	to taste		⑧ Season and drizzle with more hazelnut oil if desired. ⑨ Warm through or refrigerate until use.

(2010)

Walnut oil or other nut oils can also be used for this recipe.

EXAMPLE RECIPE

CREAMED WATERCRESS

Yields 700 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Watercress, large branches removed	450 g	150%	① Cook sous vide in 90 °C / 194 °F bath for 7 min. ② Shock in ice water, then remove from bag. ③ Puree. ④ Pass through fine sieve. ⑤ Measure 300 g of puree for recipe, and reserve.
Water	125 g	42%	⑥ Dry-blend gellan and sodium citrate, and disperse in water. ⑦ Vacuum seal solution. ⑧ Hydrate sous vide at 85 °C / 185 °F for 5 min. ⑨ Refrigerate gel stock until set.
Low-acyl gellan (Kelcogel F, CP Kelco brand)	7 g	2.3% *(1.2%)**	
Sodium citrate	2 g	0.7% *(0.35%)**	
Watercress puree, from above	300 g	100%	⑩ Combine with gel stock. ⑪ Puree.
Glucose syrup DE 40	60 g	20%	
White onion, thinly sliced and blanched	51 g	17%	
Water	21 g	7%	
Olive oil	51 g	17%	⑫ Combine with puree. ⑬ Pour into Pacojet beaker. ⑭ Freeze to at least −20 °C / −4 °F. ⑮ To serve, Pacotize once and serve cold as a garnish for roast beef, or warm and use as a sauce for roasted fish.
Maltodextrin DE 19	27 g	9%	
Egg white	24 g	8%	
Garlic, thinly sliced and blanched once in boiling water	20 g	7%	
Capers	15 g	5%	
Salt	9 g	3%	

(2008)

(% of total combined weight of the puree and subsequent ingredients*)

EXAMPLE RECIPE

PISTACHIO PUREE ADAPTED FROM ALEX STUPAK

Yields 445 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Sicilian pistachios, shelled	200 g	100%	① Soak pistachios in water for 12 h, refrigerated.
Water	125 g	62.5%	
Pistachio oil	75 g	37.5%	② Puree together pistachios and soaking water, oil, and glucose.
Glucose syrup DE 40	40 g	20%	③ Pass through fine sieve.
Salt	4 g	2%	④ Season with salt.
N-Zorbit M (National Starch brand)	2.5 g	1.25% *(0.6%)**	⑤ Whisk into puree to thicken. ⑥ Vacuum seal and refrigerate until use.

(original 2008, adapted 2010)

**(% of total combined weight of first four ingredients)*

A colloid mill works superbly for making pistachio puree, as shown on page 418. A blender or Pacojet also works.

EXAMPLE RECIPE

BLACK TRUFFLE CONCENTRATE

Yields 325 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Black winter truffles, scrubbed thoroughly and thinly sliced	100 g	100%	① Combine and puree in blender or with rotor-stator homogenizer.
Brown chicken jus see page 344	25 g	25%	② Vacuum seal puree.
Red wine (dry)	15 g	15%	③ Cook sous vide in 80 °C / 176 °F bath for 1 h.
Portobello mushroom gills	10 g	10%	④ Transfer sealed puree to ultrasonic bath if available (see page 415), and process for 30 min. If bath is unavailable, proceed with remaining steps.
Tawny port (medium dry)	10 g	10%	⑤ Refrigerate sealed puree for later use, or prepare to serve. ⑥ To serve, warm sealed puree in 80 °C / 176 °F bath for 10 min. ⑦ Remove from bag, and blend until completely smooth.
Black truffle oil (store-bought)	7 g	3.5%	⑧ Season, and serve immediately.
Champagne vinegar	to taste		
Salt	to taste		

(2009)

This puree is quite expensive and a small amount can go a long way. Use it sparingly as a seasoning for sauces and dressings. To make a more diluted puree that can be served as a garnish, use more liquid, then thicken with a fluid gel (see page 4·176) or blend into a mushroom puree (see page 5·216).

European summer and autumn truffles, Oregon truffles, and Australian truffles are all acceptable substitutes.

EXAMPLE RECIPE

CELERY ROOT MOUSSELINE

Yields 500 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Sugar	30 g	10%	① Heat to 190 °C / 375 °F to make caramel. ② Cool completely. ③ Break into small pieces.
Celery roots, peeled and thinly sliced	300 g	100%	④ Vacuum seal with caramel. ⑤ Cook sous vide in 90 °C / 195 °F bath for 1½ h.
Skim milk	100 g	33%	⑥ Combine, and bring to a simmer.
Unsalted butter	45 g	15%	⑦ Add celery roots, and puree to fine consistency. ⑧ Pass through fine sieve.
Roasted peanut oil	30 g	10%	⑨ Season puree.
Salt	to taste		⑩ Serve or cool and refrigerate until use.

(2008)

DRYING

Most fresh foods are predominantly water, which accounts for 60%–90% or more of their mass (see page 1·292). Some of the earliest forms of cooking, such as baking, evolved as a way for our ancestors to preserve foods by drying them out. Today, we tend to value these cooking techniques not for their ability to preserve but for the unique textures they yield. The crunchy crust of freshly baked bread, the crackling skin of a roast chicken, the chewiness of a strip of beef jerky, and the dense stickiness of fruit leather are all textures that we crave—and all of them are made by deliberate, controlled acts of drying.

Drying begins at the food's surface. Liquid water evaporates from the surface and diffuses as a gas into the surrounding air. The evaporating liquid draws water from deeper inside the food to the surface through a combination of molecular diffusion and capillary (wicking) action. As drying progresses, this movement slows until eventually water from the food's interior cannot reach the surface quickly enough to replace the evaporating water. When this happens, the dry zone moves deeper into the food. With enough time, the food will dry to its core.

Hygroscopic materials, called **humectants**, are often deliberately included in food products to help them retain moisture. Humectants are particularly important in baked goods, in which drying is associated with staleness. Humectants such as honey improve shelf life and texture. Of course, the same trait that is desirable in baked goods can be problematic when we are trying to dry foods.

Drying food evenly from the surface to the center is an inherently slow process. The bottleneck is the diffusion of water through the food, which is much like the diffusion of heat by conduction (see Heat in Motion, page 1·277). The main difference is that the diffusion of water is much slower than the conduction of heat—more than 100 times slower in most food.

Perhaps surprisingly, alcohol and salt readily absorb moisture under the right conditions.

Accelerating evaporation at the food surface does not help. If evaporation removes water much faster than it can move from the interior to the surface, then that surface becomes hard and dry—a phenomenon known as case-hardening. This can inhibit further drying and can leave moisture trapped inside the food.

Case-hardening is fine, even ideal, for some purposes. In baking bread and many other foods, for example, the goal is to dry the surface to a crisp crust while keeping the inside moist. But if your aim is to dry food evenly from the surface to the center, then you must use other means—and be a bit more patient.

Desiccants are hygroscopic substances used to draw water out of the air in order to keep other things dry. The most familiar desiccant is silica gel: porous packets of it are often included in the packing materials for electronics and other items that need to stay absolutely dry.

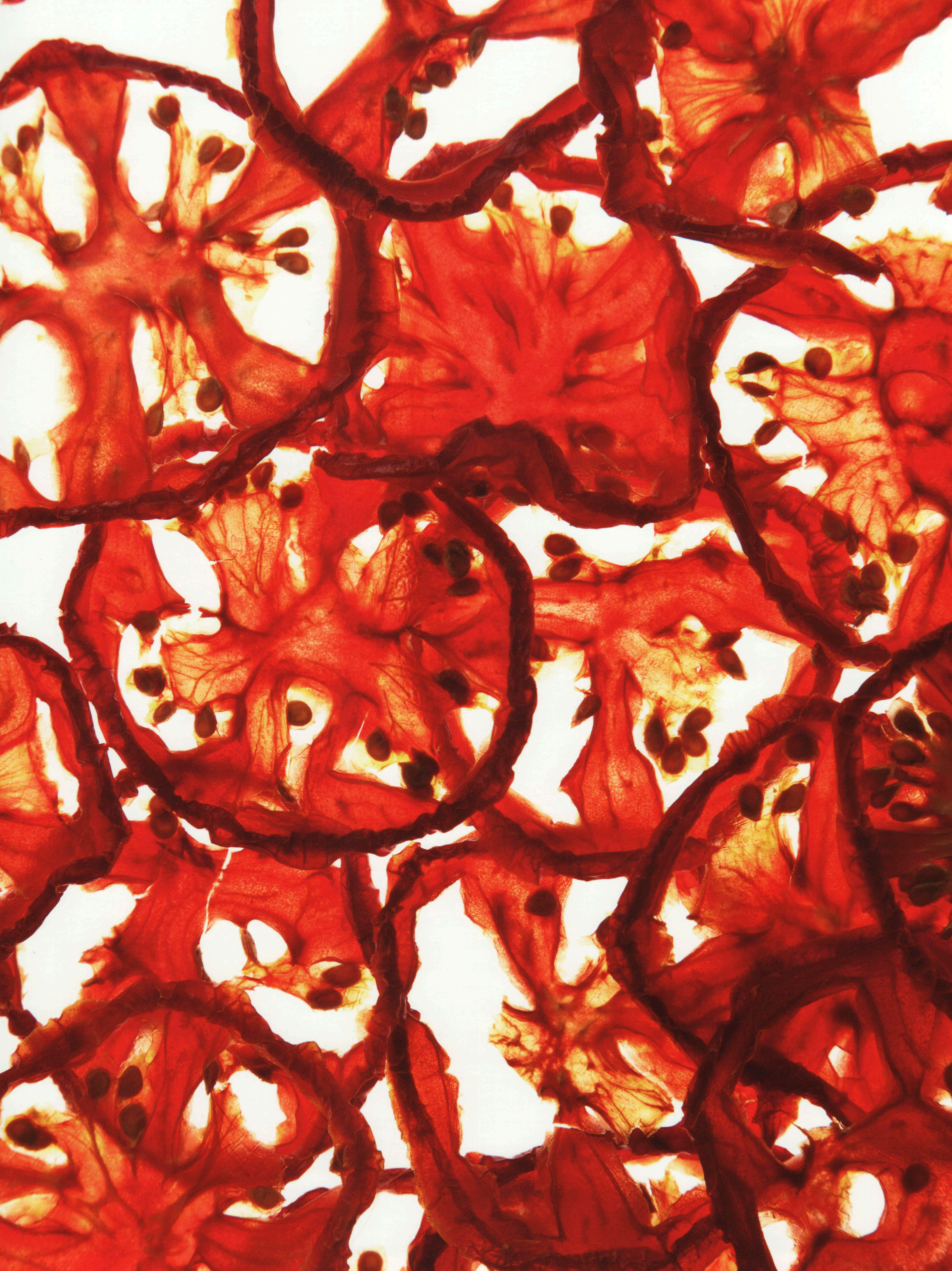
The water removed by drying needs to go somewhere. In the case of air-drying, the water vapor goes into the surrounding air. The drier the air—that is, the lower its relative humidity—the faster the food will dry. Conversely, very humid air slows the pace of evaporation, even to the point at which drying stops altogether, as discussed in Water in—and out of—Air, page 1·319.

There is another constraint on drying food. A certain fraction of the water in food is not free to diffuse or evaporate because chemical bonds tie it to various molecules in the food. This bound water is called **vicinal water** and is distinct from the "free" water in food that readily diffuses and evaporates.

The proportion of bound water in a food depends on what fraction of the food is made up of **hygroscopic** materials: substances with a strong chemical affinity for water. Nearly all common food ingredients are hygroscopic to one degree or another, especially sugars like sucrose, glucose, and fructose. Some salts used in food processing, including calcium chloride, are so hygroscopic that they will actually suck moisture out of the air and dissolve into a liquid, a process called **deliquescence.** Many other foods, including instant coffee, also show deliquescent behavior—indeed, this property is what makes them "instant."

When we dry food, we only get rid of the free moisture; the bound water stays put. With enough heat, you can unbind and drive off the vicinal water, but you might ruin the food in the process. Therefore, simple moisture content (the total percentage of a food's mass that is water) is not the best indicator of how dry a food is. Some foods can be completely dehydrated from a culinary perspective yet still contain quite a bit of vicinal water.

A better measure of dryness is the amount of *free* water in the food, which is designated by a property called water activity (see page 1·307). Pure water has a water activity of 1.0, and juices and milk have a water activity of 0.97. At the low end of the scale, crackers and dry cookies measure 0.3, and dry powders, such as powdered milk or instant coffee, have a water activity of 0.2. Dried beans typically have a water activity of 0.25.



STRATEGIES FOR DRYING

Foods react to dehydration in ways that vary from the rubbery, dense texture of a salted cucumber pickle to the brittle, powdery crunch of a freeze-dried peach. Air drying is the simplest method of drying, but it is slow and inconsistent. Dehydrators or combi ovens are better, and vacuum-assisted drying is better still—although all require special equipment.

The microwave, despite its reputation, is often the ideal tool when used at a low power that avoids scorching. Spray dryers and freeze dryers, though more exotic, achieve truly unique results. But even ubiquitous salt and sugar can effectively desiccate food, by inducing diffusion and osmosis. A quick dunk in nearly pure alcohol can dry food in a similar way.

	Application						
Strategy	Whole foods	Sliced foods	Puree	Juice or broth	Example use	Note	See page
alcohol	√	√			pickles, herbs, jerky	accelerates drying via osmosis	
combi oven		√	√		same as dehydrator; salt cod, bottarga	good control, but drying ties up equipment for a long time	162
dehydrator		√	√		leather, fruit chips, jerky	has limited heat and airflow, so thin slicing is important	431
freeze dryer		√	√	√	fruit and vegetable chips, stock powder, juice powder	best for heat-sensitive foods; can produce unique textures; very expensive	444
microwave	√	√	√		jerky, fruit and vegetable powder	can dry food rapidly, but choose the power level with care	182
salt and sugar	√	√			cured meat, vegetables	dehydrates by osmosis; good for curing and pickling	396
spray dryer				√	stock powder, juice powder	use with thin liquids that have a high solids content; often need to add bulking ingredients	438
vacuum dryer	√	√	√		pasta, dried herbs	fast, very good results for many foods	433

Drying protects food from spoilage and pathogens because it reduces water activity. Most bacteria stop growing at a water activity at or below 0.91; yeasts generally don't thrive below 0.87. That's why raisins, which have a water activity around 0.76, don't ferment into wine. Lowering water activity also suppresses many enzymatic reactions that degrade food.

If you seal a dried food in a container and let it sit for a while, the water activity of the food will come into equilibrium with the water vapor of the air in the container. Raisins with a water activity of 0.76 will be at equilibrium with air having an **equilibrium relative humidity** of 76%, for example.

This has an important practical implication for air-drying: to dry food, you need to place it in air that has a relative humidity lower than the water activity you want to reach. That means drying raisins in air at a relative humidity no higher than 76% (0.76). To dry milk, the relative humidity should be at or below 20%—at least in the final stages of the process. Drying near equilibrium relative humidity takes a long time. To ensure reasonable drying times, the relative humidity has to be much lower. Drying is thus all about keeping the humidity of the air around food well below the food's water activity so that water continually moves out of the food and into the air.

Relative humidity is a measure of how much free water is in the air and as such is conceptually related to water activity.

Dry boxes are used to store dry items and maintain their low water activity. The boxes contain desiccants such as silica gel at the bottom that absorb any remaining water vapor in the food or the surrounding air. More sophisticated dry boxes can be connected to a vacuum pump, which virtually eliminates humidity by removing air and water vapor. Dry boxes help prevent confections and other dried food from becoming sticky in a humid kitchen.

Drying with Warm Air

There are several ways to lower the relative humidity of air. The simplest is to heat it; even gentle heating lowers relative humidity considerably. This technique has been used in food-drying through the ages. Sun-drying, for example, uses solar energy to heat the food and air.

Another approach is to circulate the air. As water evaporates from food, it raises the relative humidity of the thin layer of air, called the boundary layer, that is in immediate contact with the food. Even if the air a short distance away from the food has low relative humidity, the boundary layer can become saturated with moisture and prevent drying. Circulating air with a fan disrupts the boundary layer and keeps water vapor from accumulating near the food.

Dehydrating cabinets use both of these techniques to dry food effectively and inexpensively. A cabinet-style dehydrator is a dedicated piece of equipment that gently heats and circulates air, operating reliably and with moderate control at temperatures ranging from 40–70 °C / 105–160 °F. It has a fan as well as perforated shelving to help ensure vigorous airflow around the food.

Combi ovens, discussed in chapter 8 on Cooking in Modern Ovens, are also well suited to drying. But a combi oven is much larger and more expensive than a dehydration cabinet. Unfortunately, typical convection ovens won't do for drying because they are not accurate enough at the low temperatures that work best.

Food in a dehydrator goes through several stages of drying, just as baking food does (see page 101 for a complete explanation). Knowing these stages will help you to recognize when drying is going too fast and when it is going too slowly.

During the initial, brief stage of drying, called the **settling period**, the surface of the food warms up to the **wet-bulb temperature**—the value that a wet thermometer would read. In the next phase, the **constant-rate period**, a balance is struck between the rate at which moisture inside the food diffuses to the surface and the rate of evaporation that occurs there. During this stage, the food should appear shiny and slightly tacky, but still wet, to the touch.

If drying is going too fast, the food surface will become increasingly dry and crusty, and you should lower the temperature—the food is on the

For more on wet-bulb and dry-bulb temperatures, see page 1·314.

Herbs can be dried in many ways, ranging from traditional approaches like tying them in bunches hung in the sun to more high-tech approaches like vacuum drying.

verge of baking rather than dehydrating. If the surface remains visibly wet, however, this means that the food is drying too slowly, and you should increase the air temperature (and decrease the humidity directly, if possible).

In the final stage of drying, once the bulk of the water has been evaporated, the process will often seem to stall. This is because the drying temperature is not hot enough to vaporize the tightly bound vicinal water that remains. At this stage of drying, the food is usually tacky, even sticky, and has a leathery texture. In some cases, this might be exactly what you want: the chewy texture of fruit leather or beef jerky, for example.

But if you want to drive out the vicinal water, then you must substantially increase the temperature of the drying air. You might need temperatures near, or even above, the boiling point of water to dry the food further. Such temperatures are generally beyond the capability of standard dehydrating cabinets, so you'll need to move the food into an oven or vacuum desiccator to finish the job.

Of course, high temperatures will invariably alter the texture and flavor of the food. You want to be sure that such altered textures and flavors and an advanced degree of dryness are the result you're looking for before you take these extreme measures.

It is difficult to specify exactly what combinations of temperature and humidity will work for drying any given food, but some general guidelines apply. Lower drying temperatures almost invariably yield better results than higher drying temperatures do. That's because water isn't the only thing that vaporizes during drying: volatile aromas also vaporize and degrade, and the higher the drying temperature, the more pronounced the loss. Rapid drying at high temperatures also does more damage to the texture of food.

Balanced against these restrictions are factors of expedience and food safety. You'll be tempted to use higher temperatures to get the job done sooner, and as long as evaporation doesn't outpace the wicking of water to the surface, that approach will work.

Safety issues can arise at lower drying temperatures if the temperature of the drying food itself is not high enough to halt bacterial growth. In practice, the food—not the air in the chamber—needs to stay at a temperature above 52 °C / 126 °F. Keep in mind that, for most of the drying process, food is at the wet-bulb temperature, which is generally lower than that of the air flowing past it because the food is being cooled by the evaporation of moisture from its surface.

The simplest way to abet safety as well as expedience is to slice food thinly (and spread purees thinly) to speed drying. In practice, slicing food to less than 1 cm / ⅜ in thick and dehydrating at temperatures above 40 °C / 105 °F is usually enough to minimize the proliferation of bacteria.

But short drying times at low temperatures won't *decontaminate* food. To destroy the bacteria already present in food, you must pasteurize it, and

that requires drying or cooking the food at specific temperatures for specific times (see page 1·148). Food prone to internal contamination must be adequately pasteurized at some point before eating: either before, during, or after drying..

Instead of cooking, you can use some combination of curing or fermenting to decontaminate food before drying it. These methods are commonly used for meats and seafood, in which very slow drying at low temperature (typically 15–25 °C / 60–80 °F) and high humidity (typically 75%–90% to start, but declining over time) over a period of weeks or even months yields characteristic textures.

Some foods don't need pasteurization: intact pieces of raw fruits, vegetables, and even intact muscle foods are most likely to have only surface contamination. Very brief blanching in boiling water or steam will ensure that surface bacteria have been destroyed. Another useful strategy, particularly for raw fruits and vegetables, consists of washing them in a 0.4% solution of water and bleach for one minute, followed by a thorough rinsing in clean water. This is a common practice in the agricultural world, and, so long as the bleach solution is dilute enough, it will not impart an unpleasant taste.

Even after taking these steps, however, you need to dry decontaminated food either quickly enough or at a temperature high enough to prevent bacteria from recolonizing and proliferating on the warm, tacky surface of the food.

Vacuum-Drying

Drying under vacuum is a powerful way to dehydrate food. Lowering the pressure drives water out of food just as effectively as heat does. At low ambient pressures, the boiling point of water drops dramatically; you can boil water at room temperature, and even at freezing temperatures, if the pressure is low enough.

Water also evaporates more readily at lower pressures, and drying happens faster, too. With the surrounding pressure reduced, the water inside food starts to push to the surface. The vacuum effectively "sucks" the water out of the food.

Several kinds of vacuum dryers are suitable for the kitchen. The least expensive and simplest to use is a vacuum desiccator, a piece of equipment commonly found in chemistry laboratories (see Suck It Up! on page 436). Typically dome-shaped, the container has a drying rack nested in its lower half and a valve, to which a vacuum pump connects, on its upper half. Desiccators are made either from heavy glass or from lighter-weight (and much less expensive) plastic. Our advice is to skip the glass versions: they are expensive, fragile, and difficult to seal properly. Chemistry labs use glass desiccators mainly for evaporating solvents that would erode plastic.

Another kind of vacuum dryer that cooks should know about is a fancier and larger cabinet-style desiccation box that has multiple shelves. This kind of device is a good choice for drying larger amounts of food.

Using a vacuum desiccator is simple. Place the moist food onto the drying rack, close the lid (the upper half of the dome), connect the vacuum pump to the valve using vacuum tubing, open the valve, and engage the vacuum pump. Keep the pump running until the food is dry (you can stop the process periodically and check the food).

To hasten the drying process, place the entire setup outside on a sunny day—or next to a window in bright sunlight. The sun will warm the food and accelerate evaporation. Although it may be tempting to place the desiccator under a heat lamp, don't do it if yours is plastic; it will melt!

You can also use a vacuum desiccator to store delicate foods that have already been dried. To do this, cover the bottom of the desiccator with silica gel, place the food on the rack, seal the chamber, and turn on the vacuum pump. Then close the valve and disconnect the pump. The silica gel will absorb any residual moisture that evaporates from the food or that was left inside the chamber.

A more elaborate piece of equipment for vacuum-drying is a vacuum oven. This is a vacuum chamber with shelves that can be heated. There is very little air left in a vacuum oven, so the only way to heat the food is through conduction from the shelves. It is essential that the food you are drying sits firmly on the oven shelves.

Even then, food will heat very slowly in a vacuum oven. These ovens offer some unique culinary possibilities in addition to drying, such as cooking very light meringues (see page 4·247).

The term vacuum-drying is a bit of a misnomer. Food in a vacuum continually outgases water vapor—that's the point of drying. So the environment in the desiccator isn't really a vacuum; it's a blend of low-pressure air and water vapor. "Low-pressure drying" would be a more accurate name.

Vacuum-drying removes volatiles as readily as drying at higher temperatures, because, just like water, these evaporate more readily at lower pressures. The advantage of vacuum-drying is that the remaining volatiles are not altered or degraded by excessive heat.

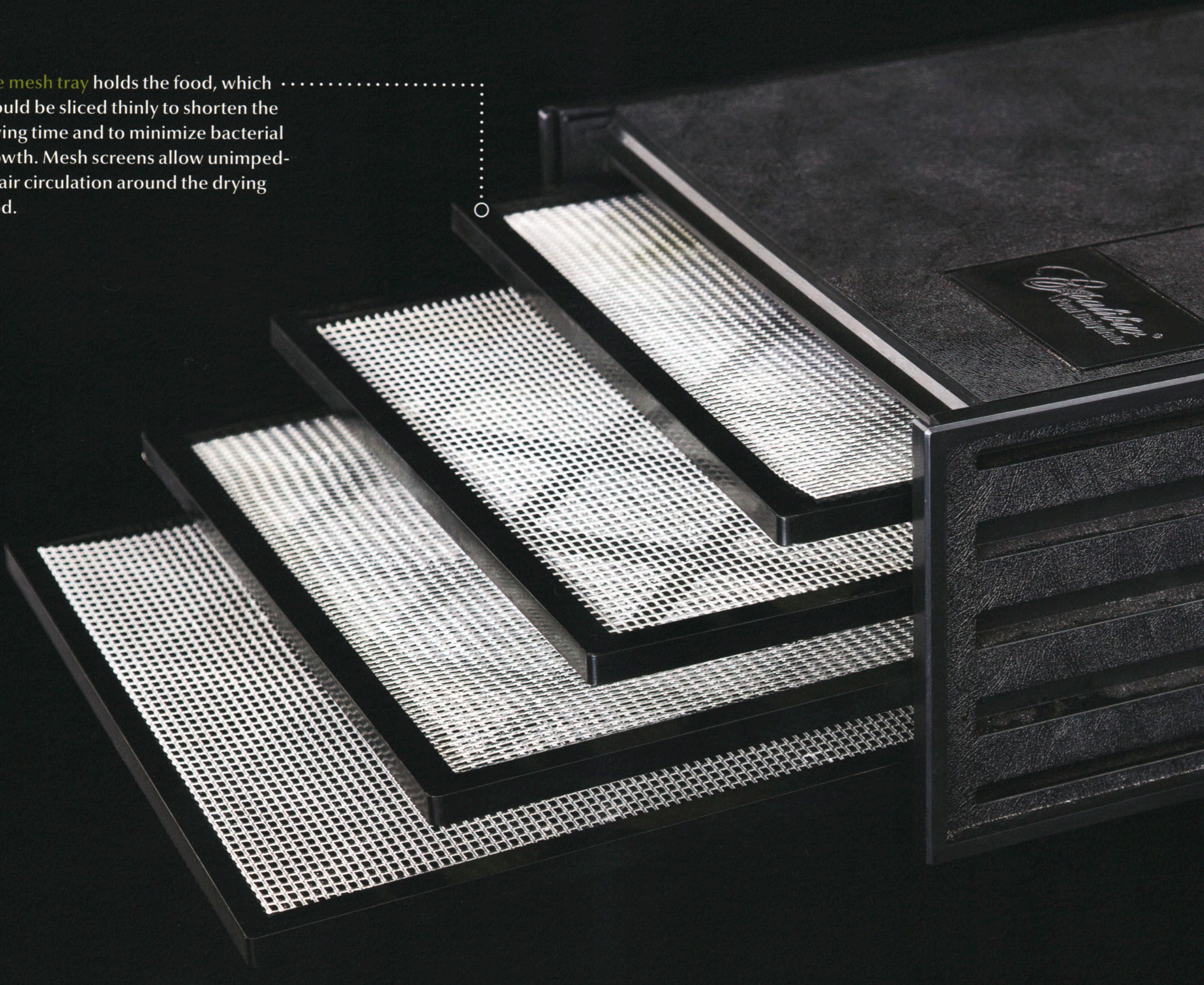
The equipment associated with vacuum-drying also provides unique ways to manipulate the texture of food by expanding foams. For examples, see chapter 16 on Foams, page 4·243.

DRY UP!

Simple dehydration is one of the oldest forms of food preparation, but innovative cooks continue to dream up novel applications for dehydrated food. Perhaps the most versatile inexpensive tool for drying foods is the cabinet-style dehydrator, which consists of a ventilated chamber, a fan, and a small heater that warms and dries the circulating air.

Fresh air blown by the circulation fan carries humid air away from the surface of the food. Warming the air lowers its relative humidity, speeding drying at the surface of the food. But avoid setting the temperature too high. Air that is too dry will evaporate water from the surface of the food faster than water can diffuse out from its center. The result is unevenly dehydrated food that has a dry, hard surface but a wet and leathery center.

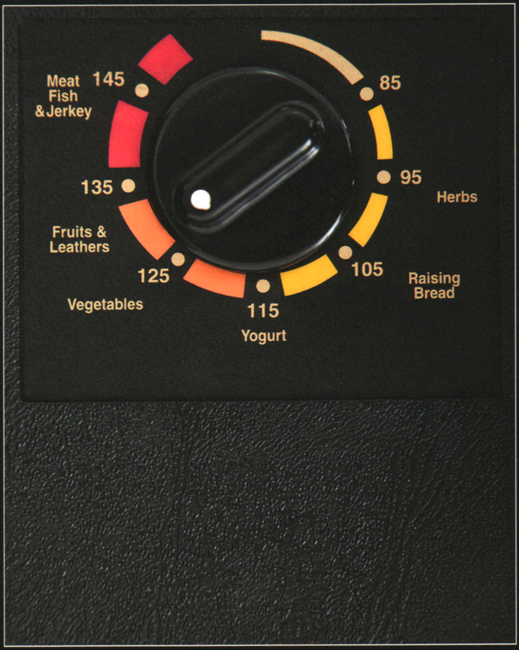
On the other hand, avoid setting the temperature too low because this can risk bacterial growth on the moist surface. If you must use low temperatures, make sure the food is sliced or spread thinly enough to dry quickly.



The mesh tray holds the food, which should be sliced thinly to shorten the drying time and to minimize bacterial growth. Mesh screens allow unimpeded air circulation around the drying food.

The dehydrator should be placed in the least humid part of the kitchen, usually a well-ventilated area. If the intake air is humid, the drying process will be less efficient.

Drying time is roughly proportional to the square of the thickness of the food. So food sliced half as thick will dry in a quarter of the original time required. Dehydration can take hours to days, depending on the initial moisture content and the dimensions of the food.



A very low power heater raises the air temperature inside the dehydrator to about 30–65 °C / 85–150 °F. Choose the drying temperature appropriate to the food and application. Higher temperatures will hasten drying up to a point, but lower temperatures and slower drying times tend to yield more even results.

Increase the temperature setting to dry the air and to warm the food enough to drive evaporation—but not so fast that the food dehydrates unevenly.

Vents on the sides of the dehydrator exhaust moist air and bring in fresh air from outside. A fan circulates the air in the dehydrator, which speeds up the process by removing air laden with moisture carried from the food and replacing it with drier air from outside the dehydrator.

When dehydrating meats and vegetables, blanch them briefly in boiling water or a sterilizing solution to kill any bacteria on the surface. This allows you to safely use a slower drying rate so that the surface doesn't harden and cause evaporation to stall.

Popular items for drying include apricots and other fruits, vegetables, herbs, and flowers, such as rose petals that have been crystallized by being coating with sugar and gum arabic (above; see page 3·368). Meats can also be dehydrated, typically after first curing them.

SUCK IT UP!

Vacuum desiccators offer a very efficient way to dry foods without resorting to high temperatures that often alter the flavors. Vacuum-dried herbs, for example, are a revelation.

The simplest kind of vacuum desiccator is a dome-shaped glass or plastic container that connects through a valve to a vacuum pump. The pump reduces the air pressure in the container, which in turn lowers the boiling point of water and speeds evaporation. The pump also continually removes moisture that would otherwise accumulate inside the chamber, so the remaining air has very low humidity.

When the pressure drops low enough, the water in the food will begin to boil even at room temperatures, which do not degrade heat-sensitive, volatile aromas. By contrast, even the mildly warm temperatures inside a cabinet dehydrator (see previous page) can alter the flavors.

Vacuum desiccators are useful for quickly drying noodles or delicate herbs and for keeping moisture-sensitive foods dry until serving. You can use them to enhance textures, as demonstrated by chef Heston Blumenthal's masterful triple-cooked potato chips, which are wonderfully crispy outside yet perfectly fluffy inside (see recipe on page 3·322). Or try expanding and then drying foams, a technique that yields a spectrum of delicate culinary creations, from ultralight meringues to edible faux coals (see page 4·314).

A tight seal must be maintained between the lid and the base of the desiccator jar. On glass desiccators, ground-glass rims and vacuum grease ensure an airtight joint. Plastic jars use a rubber gasket instead. In either case, you should always clean the joint or gasket before assembling the desiccator because any dirt or food particles may cause the seal to fail.

The side port connects to a vacuum pump, which evacuates air from the container. On the glass container shown here, twisting the side port aligns or separates holes to evacuate or seal the chamber. On plastic vessels, a separate stopcock can be rotated to accomplish the same function.

Place herbs or other foods in the container and close the lid. Thinner or more porous foods will always dry faster than thicker or denser ones.

A desiccant such as silica gel may be used to help soak up water. Although not typically needed during vacuum dessication, desiccants are useful when storing dried food in a desiccator with the vacuum port or stopcock closed.

The vacuum pump generates the suction that reduces the air pressure in the container. The pump must be able to ingest water vapor without damage. Aspirator-style pumps, either motorized (shown here) or faucet-style, usually work best. Diaphragm-style pumps will work for this purpose, too. But an oil-type pump is not a good choice because water will get into the vacuum oil, resulting in the need for an oil change. Periodically adding ice to the water in the aspirator pump chamber helps it produce a better vacuum.

Spray-Drying

Drying a liquid produces a more concentrated liquid and was discussed earlier in Concentrate!, page 379. If you want to dry a liquid into a solid powder, then spray-drying is the technique to use.

Spray-drying exploits the fact that the smaller a drop of liquid is, the faster it will dry. Spray dryers thus break up liquids into extremely tiny droplets. The business end of a spray dryer is built a little bit like a showerhead. This atomization nozzle sits at the top of a heated, silo-like or funnel-shaped chamber. A liquid solution high in soluble solids—either naturally occurring or added by the user to reach 40%–60% by mass—is injected under high pressure into the nozzle.

The liquid exits the nozzle as a fine mist that meets heated air blowing up through the drying column. The droplets dry rapidly because of their large surface area relative to their miniscule volume. They turn into a cloud of solid particles, each with a diameter of roughly 180–250 microns (millionths of a meter)—about 0.007 in. The dust-like pieces slowly settle to the bottom of the chamber, where they can be collected.

As with other methods of drying, lower temperatures are preferable to higher ones in spray-drying, because they are less damaging to flavor. The taller the tower of the spray dryer is, the lower the temperature that is necessary to dry the droplets. Greater height provides more distance and thus more time for the mist to dry before reaching the bottom. Industrial-scale spray-drying towers are truly enormous silos many stories high.

A short, lab-scale spray drier with a column about 1 m / 3 ft high typically blows air up the column at temperatures ranging from 90–300 °C / 195–570 °F. The liquid mist then cools the air in the chamber to about 100 °C / 212 °F. The evaporation of moisture from the droplets further cools them to around 40 °C / 105 °F, so that very little heat damage occurs to the drying food.

Spray dryers are very expensive. Fortunately, excellent spray-dried powders are commercially available as flavoring ingredients. Supply catalogs list hundreds of spray-dried powders in fruit, vegetable, and savory flavors. These powders make colorful, intensely flavored garnishes for dishes, and they can also be used to add a concentrated flavor to a food that would be difficult, if not impossible, to duplicate in the kitchen.

The powders rehydrate easily to yield unique products such as spray-dried sauce preparations. They can be sprinkled onto a dish like any seasoning or blended into pasta and pastries. We love them in sauces. Adding powdered blood orange juice to a traditional *sauce maltaise* is a fantastic improvement. Store all powders in an airtight environment.

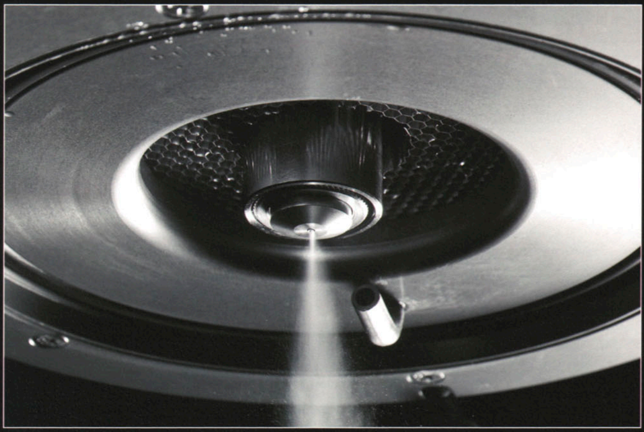
Spray drying produces a powder from a liquid—in this case, blood orange juice.

The injection nozzle atomizes liquid and sprays it into a fine mist, where it encounters hot air, which rapidly dries it into a powder.

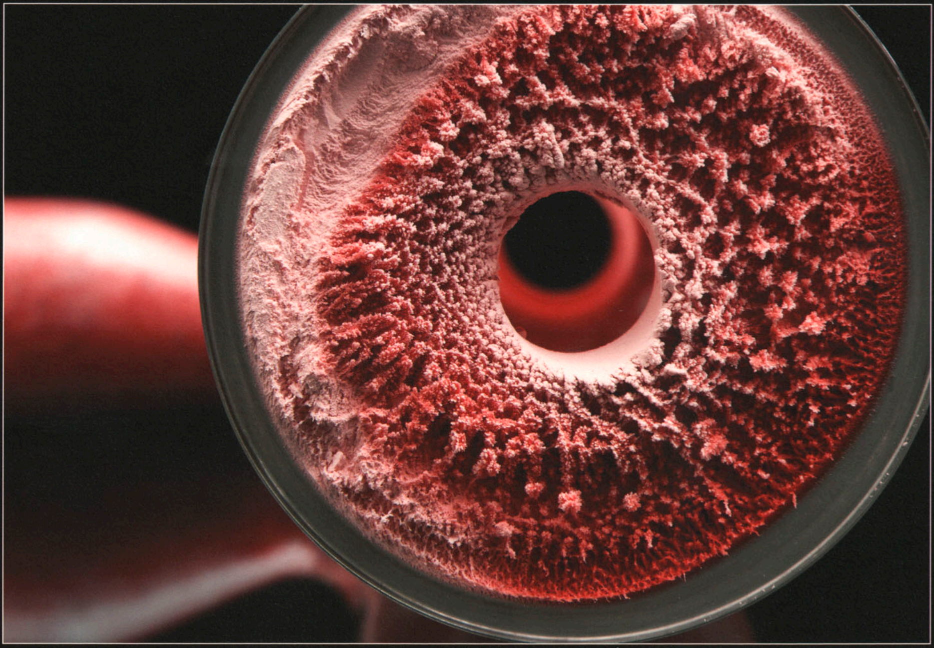
TURNING LIQUIDS INTO POWDER

Spray dryers, which dehydrate a liquid mist into a cloud of powder, are used widely in the food industry to make powdered forms of everything from milk and coffee to eggs and sauces. The pharmaceutical and chemical industries use spray dryers for mass-producing medicinal powders as well. The device works by spraying very fine droplets into a draft of hot air; the air dries the droplets rapidly by evaporation as they fall. The dry powder that results collects in a receiving flask at the bottom of the drying column. Truly adventurous cooks can use a smaller, laboratory-scale spray dryer, like the one pictured here, to make their own spray-dried powders in the kitchen.

The controls typically allow you to set the rate at which the liquid is sprayed into the chamber (via the pressure of the "atomizing air" in the spray nozzle). You can also adjust the temperatures of the inlet air, the outlet air, and the liquid itself. A fair amount of trial and error is required to find the optimal temperatures for different liquids.



The injection nozzle atomizes the fluid into a mist of droplets that range in diameter from 180–250 microns / 0.007–0.01 in.



Spray-dried blood orange juice, seen here on the base of the cyclone chamber, makes a good flavoring for a sauce or a stew.

Spray dryers enable you to "dry" essential oils that normally can't be dried directly. To accomplish this, first suspend the target oil as droplets in a water-based solution that is high in soluble solids such as trehalose or maltodextrin. Then run the mixture through the spray dryer, which effectively encapsulates the oil droplets in a crust of carbohydrate powder. This innovative process helps prevent oxidation and other chemical degradation of the oils so that they can be shipped and later dissolved in food or drink when needed.

The input flask holds the liquid that is to be dried (blood orange juice is shown). The solution must contain 40%–60% solids; if not present naturally, the concentration of solids can be increased by evaporation or by adding bulking agents such as maltodextrins or starches. For sugary juices, for example, adding a low-DE-number dextrin that does not readily absorb moisture will help the powder dry properly without becoming a sticky, clumpy mess.

The spray chamber contains hot air that flows around the injected mist. This chamber can be gigantic—80 m / 260 ft or taller—in industrial systems, such as those that make spray-dried tomato powder. The great height provides more time for the dried droplets of food to fall, so cooler drying temperatures can be used.

The cyclone chamber separates the dried, solid particles from the updraft of hot air. The whirling airflow drives the solid particles around in a circular path, causing the denser solid particles to settle to the bottom for collection. Any liquid mist and hot air is carried back to the top of the drying column through a tube.

The air inlet blows heated air up through the drying column.

The receiving flask is where the powder ends up.

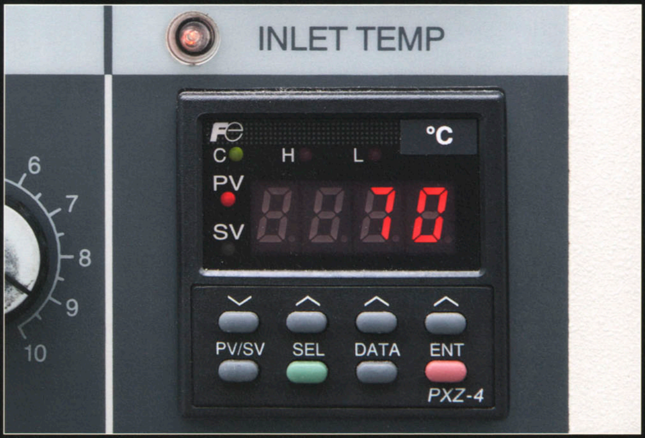
HOW TO Use a Spray Dryer

Spray dryers turn liquids into powders. A fine mist is sprayed into the top of a tall chamber, and warm air is pumped upwards from the bottom of the chamber with just enough pressure to keep the tiny droplets aloft until they dry and gradually fall. The solid particles settle at the bottom of the chamber and are pulled into a receptacle by a vacuum.

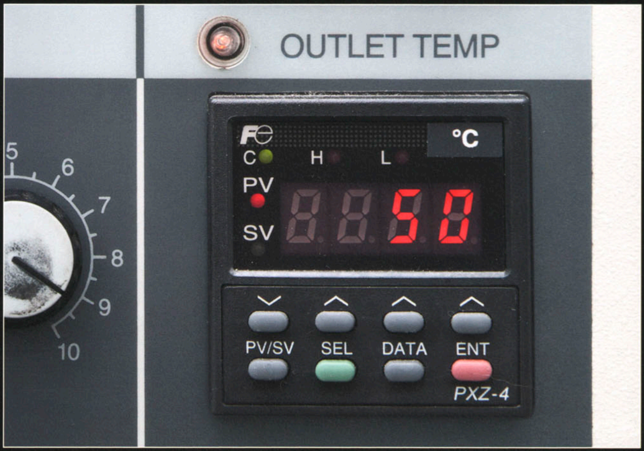
The amount of dissolved solids in a liquid determines how much powder results from spray-drying. If a liquid is mostly water, it will dry into almost nothing. If the liquid isn't naturally high in dissolved solids, you can add bulking agents to give it more body and to prevent sweet mixtures from sticking together. Good choices for bulking agents are maltodextrin and trehalose, but you may need to do some experimenting to find what works best for your application.

Generally, liquids should either be preconcentrated or bulked before spray-drying to 40%–60% dissolved solids by mass. Store all spray-dried powders in an airtight environment, or they will absorb atmospheric moisture. Many food powders also benefit from being stored in a dark or opaque container because light can degrade them.

1 **Prepare the liquid.** Add a bulking agent and any flavoring as needed. Place the liquid into the intake system of the spray dryer.



2 **Set the temperature of the liquid spray.** Use the dial at the top of the machine to set the spray or inlet-control temperature. We have found **70** °C / **160** °F to be a good starting point for kitchen-scale machines.



3 **Set the air temperature or outlet temperature.** The control is at the base of the machine. Start at **50** °C / **120** °F.

4 **Begin spray-drying.** The powder will collect in a receptacle at the bottom of the machine. If the liquid is too wet and sticky, or if it clumps, increase the amount of bulking agent, and set the inlet and outlet temperatures **5–10** °C / **10–20** °F higher.

EXAMPLE RECIPE

SPRAY-DRIED BUTTERMILK

Yields 200 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Buttermilk	2 kg	100%	① Blend together thoroughly.
Dextrose DE 36	20 g	1%	② Set spray dryer's inlet temperature to 90 °C / 194 °F. The outlet temperature should read about 57 °C / 135 °F.
Microcrystalline cellulose (Avicel CG 200, FMC BioPolymer brand)	20 g	1%	③ Spray-dry at full pressure until liquid is fully processed, about 2 h.
Lactic acid	0.4 g	0.04%	④ Store powder in airtight container.

(2010)

EXAMPLE RECIPE

SPRAY-DRIED BLOOD ORANGE JUICE

Yields 250 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Blood orange juice, clarified	2 kg	100%	① Blend together thoroughly.
Maltodextrin DE 9	100 g	5%	② Set spray dryer's inlet temperature to 100 °C / 212 °F. The outlet temperature should read approximately 65 °C / 149 °F.
Citric acid	20 g	1%	③ Spray-dry at full pressure until liquid is fully processed, about 2 h.
			④ Allow spray dried juice to cool completely. If powder clumps, grind in coffee grinder, and try adding more maltodextrin and using a higher drying temperature for the next batch.
			⑤ Store powder in an airtight container.

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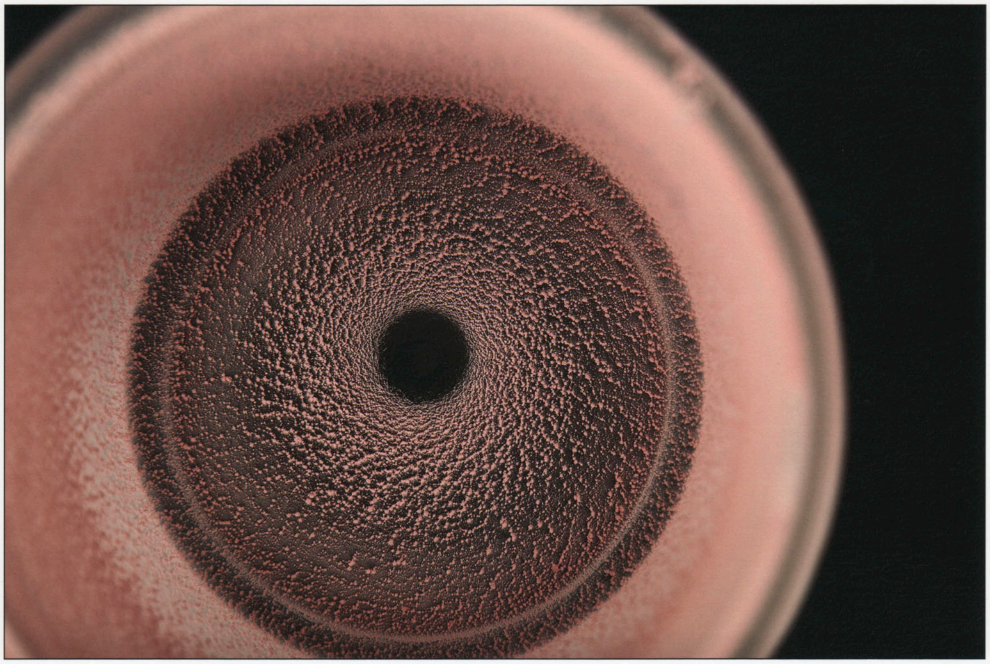
Evaporative cooling keeps the juice much cooler as it dries than the outlet temperature would suggest.



Cyclone separation is used to centrifugally separate the powder from the air stream. This process results in an interesting pattern. After being removed from the receiving flask, some foods may need to be pressed through a sieve to ensure good particle size distribution.

Freeze-Drying

As we noted in the previous section, vacuum-drying works in part because the boiling point of water falls as pressure declines—it falls so much, in fact, that at very high vacuum (and thus very low pressure) water will even boil at temperatures below 0 °C / 32 °F. Consequently, if you freeze a food solid and then lower the pressure while maintaining freezing temperatures, the water in the frozen food will begin to "boil." More precisely, the water will turn directly from ice into vapor without melting into a liquid first. This process, called sublimation, is described in more detail in Sublimation and Deposition, page 1·326. As a practical matter, sublimation offers an additional way to dry food: **freeze-drying,** also called **lyophilization.**

Sophisticated (but expensive) freeze dryers use microwaves to slowly heat the food. Heated shelves are a simpler and less expensive option.

Freeze-drying is used by conservators at museums and rare-book libraries to restore water-soaked books. Once freeze-dried, the paper is restored to nearly new condition.

Freeze-drying works by freezing the food and then slowly warming it under a high vacuum (below 6 mbar / 4.5 torr) until the ice crystals in the food sublimate. Once vaporized, the water moves out of the food and is trapped by refreezing onto a very cold condenser that is connected to the main chamber. This sublimation process is the main step of freeze-drying, and it goes very slowly.

After sublimation, a small amount of water remains chemically bound to the surface of proteins and other molecules that make up food. Removing this trapped, or vicinal, water to completely dry the food requires a second step at a higher temperature (see Freeze-Drying, page 450).

If the food appears to "melt" or foam on the surface during sublimation, it has risen above its critical temperature. Decrease the pressure in the chamber to speed sublimation, which will quickly cool the food down. At the same time, lower the shelf temperature by 5 °C / 10 °F, and continue the freeze-drying.

Freeze-drying provides a way to preserve food so that it doesn't need refrigeration and can later be rehydrated to something resembling its fresh state. In freeze-drying—unlike cooking, curing, or other forms of drying—it is possible to remove water from food with minimal changes to the intricate and delicate microstructure of the food. Possible but not easy: it requires care to do the least damage while freeze-drying, and care must also be taken when rehydrating the food later.

Dried food isn't like fresh, and even if we add water to rehydrate it, it is never the same. When food dries, the liquid water in it moves, exerting capillary forces on cell walls or membranes. The resulting damage is often all too evident.

Note that the critical temperature for freeze-drying is a totally different concept than the critical temperature on a phase diagram (see page 1·328). It is unfortunate that these different entities share the same name. For more on the critical temperatures of common foods, see the table on page 451.

Conventional drying (whether under a vacuum or not) causes water to move within the food in liquid form; it only evaporates near the surface. In freeze-drying, however, water changes directly from solid to gas throughout the food, not merely at the surface. Done right, no liquid water forms, no capillary forces are exerted, and much less damage to delicate food structure occurs.

You can freeze-dry food directly from the raw state or after cooking. Regardless of the starting point, the first step for freeze-drying is always *freezing* the food—and it is essential to do so as completely as possible.

This is more complicated than it seems because as the water freezes, the remaining unfrozen water requires an ever-lower temperature to freeze. That unfrozen water has to hold all of the sugars, proteins, carbohydrates, and other molecules that are dissolved in it, and the more concentrated these solutes become, the further the freezing point of the water is depressed. Eventually, the remaining water is so saturated with dissolved molecules that it simply won't freeze; instead, it becomes glassy, supercooled liquid water.

The temperature at which this change occurs is known as the **glass transition temperature**. For the best results, you must get the frozen food several degrees below this temperature before you freeze-dry it. For meats and seafood, the glass transition temperature is somewhat higher than −20 °C / −4 °F, but in foods such as fruits, it can be much lower.

The rate of freezing is important, too. Although slowly frozen food freeze-dries more quickly (because slow freezing produces bigger, more connected ice crystals), quickly food frozen gives the best results. You'll want to strike a practical balance between reasonable freeze-drying times and the highest-quality result.

Once the food has been frozen, sublimation can proceed in the freeze-drying chamber under low pressure. Sublimation, as a form of evaporation, cools the food. So the machine adds a bit of heat to drive the process, usually by heating the shelves that the frozen foods sits on.

It is important—but also tricky—to select appropriate shelf temperatures that are warm enough to keep sublimation going but not so warm that vapors accumulate faster than they can diffuse. Vapor build-up can cause ice to melt into water that flows and damages cellular structures. Any flowing water can also degrade the flavor by allowing too many of the food's aromatics to vaporize and escape. Trial and error are often needed to find the right process for a particular preparation.

Instant ramen, that hallmark dish of freeze-drying, is usually seen as pedestrian despite the great skill and science that went into its creation. But instant ramen transcended its humble reputation when Nissin Foods developed "astronaut ramen" in 2005 and sent it into orbit with Japanese astronaut Soichi Noguchi. For our take on a 21st-century ramen that upgrades the ingredients and stays down to Earth, see page 5·247.

Frozen juices and purees can be difficult to freeze-dry efficiently. As the surface freeze-dries, it tends to leave few cracks and pores for sublimating water vapor from deeper inside the food to escape through. Foaming the juice before freezing it creates an aerated structure that freeze-dries readily. Alternatively, grinding the frozen liquid or puree into smaller pieces of ice increases the surface area relative to the volume. Both of these approaches are good strategies for efficiently freeze-drying for a high-quality final result.

Sublimation causes the temperature to drop because it is another form of evaporative cooling.

As you experiment, however, it helps to know the glass transition temperature of the food you are working with because above that point, damage becomes likely. Freeze-drying experts actually refer to this temperature as the **critical temperature** or **collapse temperature**. It is so important to maintain the freeze-drying food below that temperature until it has dried, but not too far below, or the freeze-drying process will stall.

Meats have a critical temperature of roughly −12 °C to −10 °C / −14 to −10 °F. Critical temperatures for seafood can range from −12 °C to −5 °C / 10–23 °F. For plant foods, the critical temperature is often as low as −50 °C to −35 °C / −58 °F to −31 °F.

So you want to keep the food below its critical temperature but also to keep the shelves *warmer* than the critical temperature in order for sublimation to proceed apace. Now you see why freeze-drying can be tricky. Although it might seem like the shelf should eventually warm the frozen food above the food's critical temperature, it doesn't. Conveniently, the sublimation causes the water content of the food to fall, and that forces the critical temperature of the food to rise in response.

Most freeze dryers have thermocouple junctions that continuously measure the core temperature of the freeze-drying food. This feature allows you to monitor the slow progress of the drying. The usual pattern is that the temperature falls at first as sublimating water cools the food. Then the core temperature slowly increases toward the shelf temperature. That recovery from the initial dip indicates that sublimation is progressing.

When the temperature of the food nears that of the shelves, most of the ice in the food has sublimated, and the first stage is nearly complete. The next step is to warm the shelves further to drive off the last bit of the frozen water in the food. The primary stage of freeze drying is done when the core temperature of the food is above 0 °C / 32 °F. By then, all of the ice will have sublimated to vapor.

As in any kind of drying, the rate at which food freeze-dries depends largely upon its size. This inherently slow process gets much slower as food gets bigger, and thicker layers of already-dry material impede sublimating water vapor from leaving the food.

You can speed the process by slicing your food into pieces as small and thin as possible. Slices about 6 mm / ¼ in thick will freeze-dry in about four hours. Double the thickness to 1.2 cm /

Hot water rehydrates a freeze-dried ramen and dissolves its packaging, turning it into something you can eat.

½ in, and drying will take roughly 16 hours. In general, the freeze-drying time required increases somewhat faster than the square of the thickness. It's not at all uncommon for something as thick as a steak to take several days to freeze-dry.

The final stage of freeze-drying, usually called the secondary step, is to drive off the last bit of vicinal water, which requires a lot more energy than sublimation does because it means breaking chemical bonds. In this stage, you want to increase the temperature of the food as much as you dare without cooking it or damaging its flavor.

At a minimum, increase the shelf temperature to room temperature; the higher you can get away with, the better. To speed things along, you also want to dial in the lowest vacuum pressure available on the machine. You can increase the strength of the vacuum by setting the condensing chamber control to the lowest temperature the machine offers.

Once drying is done, store the food in the driest possible environment. Freeze-dried foods are so dry that they tend to absorb moisture right out of the air. The more hygroscopic the components of the food are, the greater this tendency. Foods with high sugar content, for example, can start rehydrating and become soft, even soggy, in a matter of minutes, whereas starchy foods stay crisp for hours.

Vacuum packing the food in a rigid storage container is one way to avoid this problem. Alternatively, store the food in a modified atmosphere; injected gasses are entirely dry. If nothing else, a tightly sealed container with a desiccant such as silica packets can work.

Freeze-dried foods can be eaten without rehydrating or cooking, but keep in mind that the same food safety rules that apply to dehydrating food also apply to freeze-drying. Bacteria that contaminate food can survive freeze-drying, and they will revive and start to proliferate as soon as the food begins to rehydrate.

Finally, keep in mind that rehydration requires care and good judgment. When rehydrating muscle foods, for example, use water at the same or a lower temperature than you would cook them at if they were fresh. For plant foods, hot but not simmering water does a better job of restoring the texture and flavor.

Careful rehydration is necessary only when you want to preserve the original texture of the food. For freeze-dried broths and purees, the temperature of the water isn't critical because there is no intricate microstructure left to preserve.

Fat does not freeze-dry, so freeze-dried fatty cuts of meat tend to go rancid quickly. To minimize this problem, always prefreeze these cuts of meat as quickly as possible, and after freeze-drying, store them at cool temperatures and out of direct sunlight.

Foods that contain very high levels of sugar and gelatin are also difficult to freeze-dry well. They hold on to water so tightly that, after sublimation, they are still moist enough to be sticky and soft. A high-temperature secondary drying step is essential for removing the residual water to attain a dry, crispy texture.

Freeze drying is widely used to preserve flowers because it keeps their shape and color much better than conventional drying does.

DRYING IS SUBLIME

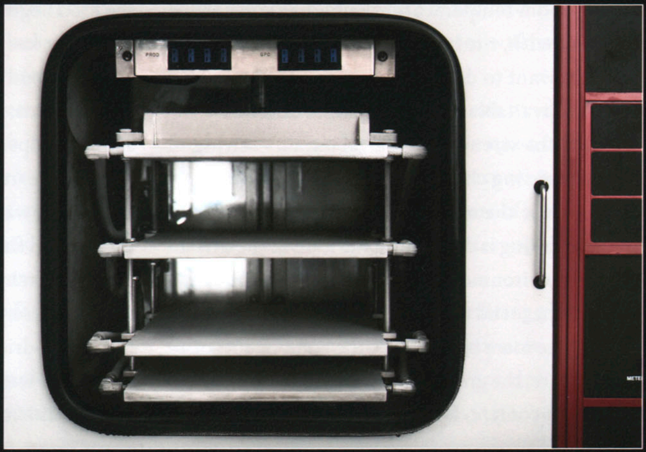
Freeze dryers remove moisture from frozen food by thawing it slowly at very low pressures. Under these conditions, the frozen water in the food sublimates into water vapor—that is, it changes directly from solid ice to water vapor without becoming a liquid. Freeze dryers exploit the same principles as vacuum desiccators, but they use even lower pressures and freeze the food before drying begins.

Drying food this way preserves flavor and texture well, because more flavor compounds remain in the food and less cellular damage occurs than in other dehydration methods.

Commercial freeze dryers were designed for pharmaceutical labs—or in the case of less sophisticated models, for florists and taxidermists—not for kitchens. But both the chamber-style device shown here and the less expensive flask-style freeze dryers work perfectly well for cooking purposes.

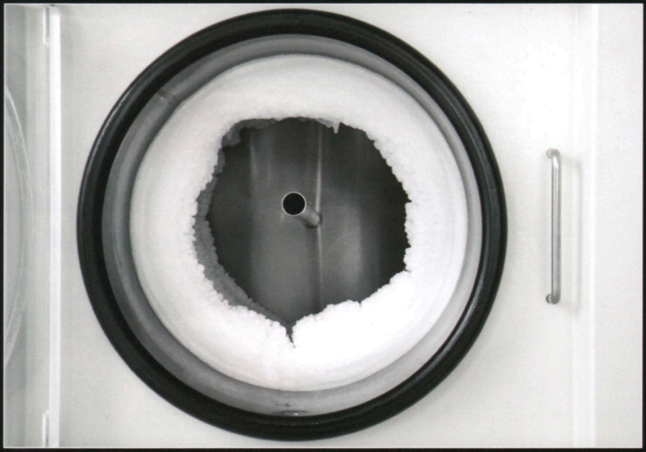
It is important to freeze food completely and to the right temperature—which is often surprisingly low—before placing it in the freeze dryer (see Freeze-Drying, page 450). You then use the machine to warm the food at just the right rate for the best result. In the final stage, the nearly dry food is heated to vaporize the last bit of residual water bound tightly to its surface.

Control units vary widely from one model of freeze dryer to another. But all devices allow you to set the vacuum pressure, the shelf temperature, and the condenser temperature.



The shelves are temperature-controlled. Typically, you set them initially to about **20** °C / **36** °F above the critical freezing temperature of the food; they then supply the heat that drives the sublimation process. You later increase the temperature as much as is practical to finish drying the food.

The thinner the food, the faster the process. Foods that are high in sugar or fat can pose challenges. Fruits can become leathery and sticky unless you infuse them with bulking agents like maltodextrin. Freeze-drying high-fat foods can make them go rancid faster because oxidation reactions accelerate.



After the water in the food sublimates, it refreezes as ice on the coldest thing around, which is the condenser (also called a cold trap)—not the food. For freeze dryers of moderate size, the capacity of the condenser ranges from 5-25 kg / 11-55 lb and limits how much food the dryer can process at once.

Food placed in the freeze dryer should be fully frozen—either in the freeze dryer itself or in a separate freezer beforehand —before the drying process begins. Fully frozen means that the temperature is several degrees below the critical temperature of the food, as described on page 453.

Vacuum pumps inside the machine produce a very high vacuum. Often two pumps are used: the first to lower the air pressure to roughly 5 mbar / 3.8 torr, and a second to drop the pressure further to 0.001 mbar / 0.0008 torr. At that extremely low pressure, the water sublimates readily.

The condenser (also called a cold trap) is essential to freeze-drying, because it pulls the sublimated water vapor out of the air as ice, thus preventing vapor from accumulating and squelching the sublimation process. The cold trap should always be colder than the food; usually, it is set between −80 °C and −40 °C / −110 °F and −40 °F. Defrost and clean the trap after each use.

PARAMETRIC RECIPE

FREEZE-DRYING

Freeze-dried foods are unlike any other. They are brittle and explosive with bold, fresh flavors and bright colors but are devoid of moisture. Freeze-drying works beautifully with fresh fruits and vegetables. Stocks can be concentrated into dry cubes with all the vibrancy of a fresh preparation and none of the saltiness of commercial bouillon cubes. Meats and seafood, freeze-dried when they are cooked and tender, will reconstitute into forms and textures remarkably similar to their fresh counterparts. And for creating unique and unexpected presentations, freeze-drying is unparalleled. Arzak in San Sebastián, Spain, was one of the first restaurants to experiment with the process.

To get good results from a freeze dryer, the most crucial step is the initial freezing. The formation and development of ice crystals are key to how the cellular structure withstands the freeze-drying and rehydration process (see page 1·304). Freeze the food in a traditional or laboratory freezer or even in liquid nitrogen. Oily or fatty foods should always be frozen very quickly for best flavor and results. Refer to Prefreezing Temperatures for Freeze-Dried Foods, next page, for our recommendations.

Once the ingredients are frozen, set the temperatures of the shelf compartment and the condenser. Because freeze-drying is done in a vacuum, there must be contact between the cold shelf and the tray that holds the food. We like to use disposable aluminum foil trays.

Storage of freeze-dried foods is important. They are so dry that they will absorb atmospheric moisture. Store all foods in a dark, completely airtight environment. Adding a desiccant will help. Take care in rehydrating the foods you have taken so much time to prepare. Meats can easily become overcooked by rehydrating at high temperatures or even at the temperature of boiling water. Fruits and vegetables also are best not rehydrated in boiling water. Grind up anything that isn't pretty, and use it as a powder.

MAKING FREEZE-DRIED FOODS

1 **Prepare the ingredients.** Cut the food into bite-size pieces or thin slices to greatly reduce drying times. Arrange the food in a single layer on conductive trays that fit in your dryer. Aerate liquids and purees before freezing or grind them into small pieces after freezing.

2 **Prefreeze the food to below the critical temperature.** See the table Prefreezing Temperatures for Freeze-Dried Foods on the next page for suggested temperatures. Faster freezing will yield better texture but will slow sublimation. Some foods have critical temperatures so low that liquid nitrogen or a laboratory freezer is needed to reach them.

3 **Set the freeze dryer temperatures.** Set the shelf temperature to 20 °C / 36 °F above the critical temperature of the prefrozen food. Set the condenser to 20 °C / 36 °F below the critical temperature.

4 **Freeze-dry the food.** Insert a fine temperature probe into the core of the frozen food. Engage the vacuum pump, and run it until the core temperature of the food is within 1 °C / 2 °F of the shelf temperature. Because of the physics of freeze-drying, the core temperature of the food may fall at first. This is not unusual. But if the core temperature of the food fails to increase within a few hours, increase the shelf temperature by 5 °C / 10 °F to supply more energy.

5 **Increase the shelf temperature to 5 °C / 40 °F.** When the core temperature of the food exceeds 0 °C / 32 °F, preliminary drying is complete.

6 **Begin secondary drying.** Set the condenser to the coldest temperature available and increase the shelf temperature to the temperature recommended in the table on the next page, or 20–60 °C / 70–140 °F (as warm as the food will tolerate without damage). When the core temperature of the food reaches the shelf temperature, freeze-drying is complete.

Prefreezing Temperatures for Freeze-Dried Foods

	Freeze to below	
Ingredient	(°C)	(°F)
fruit	−45	−49
eggs	−40	−40
ice cream	−35	−31
vegetables	−30	−22
meat	−25	−13
pastas, grains, and legumes	−20	−4
stocks, broths, and sauces	−20	−4
seafood	−15	5

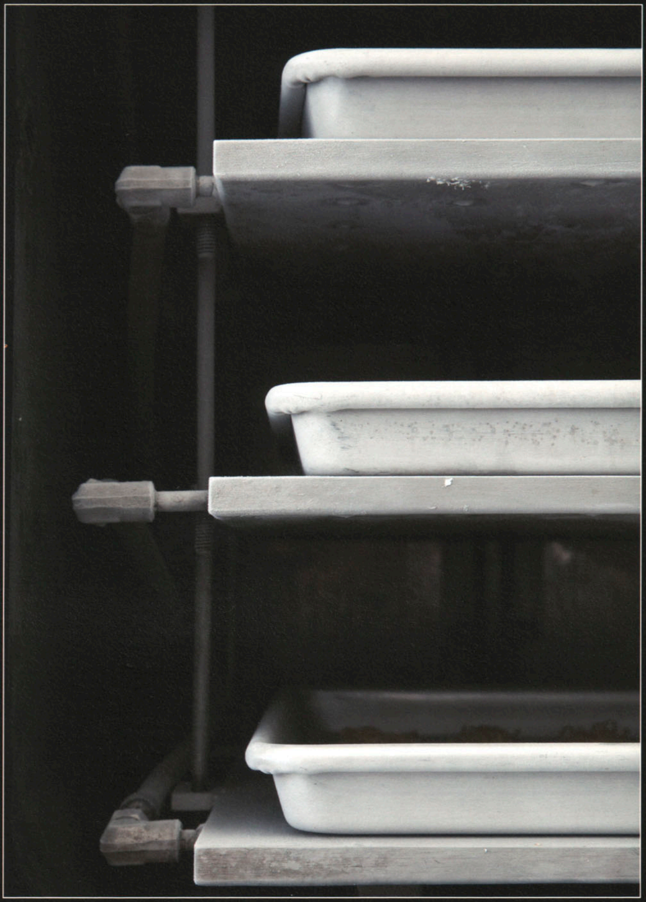
When freeze-drying liquids such as stocks, grind the frozen liquid before spreading it out as a thin layer for much faster drying. A Pacojet does a good job on the grinding.

Best Bets for Freeze-Drying

				Drying temperatures							
				Primary				Secondary		Total drying time	
		Dimension		Shelf		Condenser		Shelf			
Ingredient	Prep	(cm)	(in)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)	(h)	Example use
beef	raw, sliced	1	⅜	−20	−4	−45	−49	30	86	8	grind to a fine powder, and use to form a meaty crust on steaks and hamburgers
beef tenderloin	raw, pounded paper-thin			−20	−4	−45	−49	30	86	4	break into "carpaccio chips," and dust with olive oil, grated Parmesan, and arugula powder
eggs	cooked, peeled	sliced or quartered		−35	−31	−60	−76	60	140	12	Astronaut Ramen
fruits	sliced	0.1	1⁄32	−40	−40	−65	−85	30	86	4	enjoy whole; use in cereal or as a garnish or seasoning
	pureed	1	⅜							8	
	chunks	2	¾							64	
ice cream	sliced	2.5	1	−30	−22	−55	−67	40	104	96	sold commercially as astronaut ice cream
lettuce and tender greens	leaves	whole		−25	−13	−50	−58	40	104	12	Caesar Salad (see page 3·373)
lobster	raw, whole, shelled			−10	14	−35	−31	20	68	120	reconstitute in melted butter; grind to a powder, and use as a seasoning
noodles	cooked	0.1	1⁄32	−15	5	−40	−40	70	158	12	Astronaut Ramen
pork belly	cooked or raw, thinly sliced	0.5	¼	−20	−4	−45	−49	30	86	6	
pork shoulder	cooked tender, shredded			−20	−4	−45	−49	30	86	12	
scallops	raw, pureed			−10	14	−35	−31	20	68	8	grind to a fine powder, and use as a seasoning
	whole									48	break into panko-like slivers, and use as a breading or garnish
stocks, broths, and sauces	cubed	2	¾	−15	5	−40	−40	70	158	36	instant bouillon, breading; use to enrich soups and sauces
	ground	1	⅜							8	
vegetables	fine julienne			−25	−13	−50	−58	40	104	4	Astronaut Ramen, breading, onion tart, instant potato flakes
	minced									4	
	sliced	0.1	1⁄32							4	
	mushroom caps	whole								24	
	pureed	1	⅜							8	

Common Problems when Freeze-Drying

Problem	Possible cause	Solution(s)
collapsed or distorted shape; foamy surface	improper prefreezing temperature	refer to table of prefreezing temperatures on previous page
		increase shelf temperature more slowly during initial freeze-drying
stickiness	water remains molecularly bonded to the food	heat at a higher temperature during the secondary freeze-drying step
		add bulking agents such as starch or maltodextrin
torn or shredded skins on fruits and vegetables	skin freezes at a different temperature than the rest of the fruit	prick skins all over with a needle before freezing
rancid aroma	fatty foods can go rancid more quickly during freeze-drying	prefreeze foods quickly
		consider infusing food with antioxidant solution (see page 338)
takes too long	pieces are too large	cut pieces into smaller, more uniform cubes
	shelf is too cold	increase shelf temperature by **5** °C / **9** °F
core temperature will not rise	sublimation has stalled	increase shelf temperature by **5** °C / **9** °F
core temperature is dropping	sublimation is too fast; normal unless the core temperature of the food continues to drop for more than 1 h	reduce shelf temperature by a few degrees
		increase the temperature of the compressor



THE SCIENCE OF

Critical Temperatures for Freeze-Drying

Freeze-drying is such an inherently slow process that a part of the art of doing it is finding ways to speed things along.

Should you raise the temperature as high as you can? As long as the pressure is low enough, it should in theory be possible to slowly raise the temperature of the drying food to the normal freezing point of water without melting any ice. The extra heat would instead greatly accelerate the sublimation of the ice crystals in the food.

But each frozen food has a certain temperature, known as its critical temperature, above which some of the unfrozen water in food begins to flow. When that happens, the integrity of the food's internal microstructure gives way to irreparable collapse, slashing the rate of vapor transfer to and from the surface. Once the critical temperature is reached, the drying process effectively comes to a stop.

Critical temperatures vary. For tomatoes, the magic number is −41 °C / −42 °F; for cheddar cheese, −24 °C / −11 °F; and for beef, −12 °C / 10 °F.

Those experienced with the intricacy of freeze-drying know that it takes a good deal of experimentation to find, for each food and each machine, the right combination of frozen-food temperature, chamber pressure, and cold-trap temperature that yields the best results in the shortest time.

EXAMPLE RECIPE

FREEZE-DRIED BEEF GRAVY GRANULES

Yields 200 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Beef shank, ground	1.2 kg	160%	① Panfry; brown until dark.
Neutral oil	100 g	13.3%	② Remove beef from pan, and reserve. ③ Measure 50 g of rendered suet and reserve.
Carrots, thinly sliced	150 g	20%	④ Prepare vegetables as noted.
Button mushrooms, thinly sliced	100 g	13.3%	⑤ Brown vegetables together in suet until deep amber.
Leeks, thinly sliced	100 g	13.3%	
Sweet onions, thinly sliced	100 g	13.3%	
Turnips, thinly sliced	100 g	13.3%	
Garlic heads, split	75 g	10%	
Rendered suet, from above	50 g	6.7%	
Red wine	150 g	20%	⑥ Deglaze vegetables.
Brandy	50 g	6.7%	⑦ Add browned beef.
White beef stock see page 296	1 kg	133%	⑧ Transfer beef and vegetable mixture to pressure cooker. ⑨ Add stock, and pressure-cook at a gauge pressure of 1 bar / 15 psi for 1 h. ⑩ Strain through fine sieve. ⑪ Pour strained stock into centrifuge bottles. ⑫ Centrifuge at 27,500*g* for 1 h, and strain through fine sieve. ⑬ Measure 750 g of stock, and cool.
Centrifuged beef stock, from above	750 g	100%	⑭ Disperse gelatin into cold stock, and warm to dissolve gelatin. ⑮ Pour stock into a 30.5 cm by 20 cm / 12 in by 8 in hotel pan, and freeze completely.
160 Bloom gelatin	7.5 g	1%	⑯ Wrap frozen stock sheet in cheesecloth. ⑰ Place perforated hotel pan (30.5 cm by 20 cm / 12 in by 8 in) onto another hotel pan that is the same size but deeper. ⑱ Lay wrapped frozen stock sheet flat on perforated pan; allow thawing stock to drip down into deeper pan below it. ⑲ Freeze-dry clarified broth for 12 h, by using the table on page 450.
For rehydration:			
Freeze-dried beef gravy granules	12 g	1.6%	⑳ Mix together.
Ultra-Sperse A	8 g	1.1%	
Salt	2 g	0.3%	
Water, boiling	120 g	16%	㉑ Whisk into dry blend. ㉒ Divide gravy into four servings.

(2009)

EXAMPLE RECIPE

SALTED, FREEZE-DRIED LOBSTER

Yields 20 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Water	100 g	167%	① Mix until dissolved.
Salt	7 g	12%	
Lobster tail	60 g	100%	② Brine, refrigerated, for 12 h. ③ Cook sous vide in **57** °C / **135** °F bath for 20 min. ④ Freeze dry for 12 h, by using the table on page 450. ⑤ To use as a seasoning, grate the dried lobster over food.

(2008)

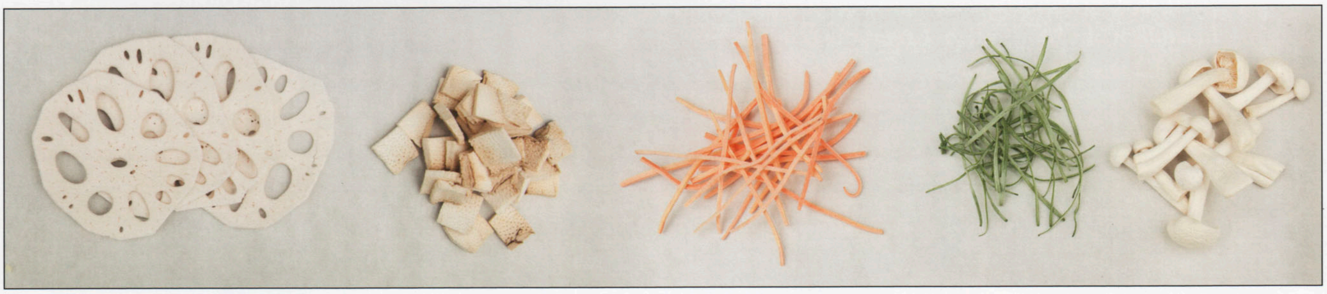
EXAMPLE RECIPE

RAMEN VEGETABLES

Yields 50 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Mirin	205 g	205%	① Combine, vacuum seal, and cook sous vide in **80** °C / **176** °F bath for 2 h.
Water	205 g	205%	② Cool.
Soy sauce	105 g	105%	③ Strain; discard liquid.
Bamboo shoots	100 g	100%	④ Slice bamboo shoots 1 mm / 1/16 in thin.
Sugar	50 g	50%	⑤ Freeze-dry by using the table on page 450.
Carrots, fine julienne	100 g	100%	⑥ Blanch for 30 s.
			⑦ Shock in ice-water bath.
			⑧ Freeze-dry as above.
Young ginger, minced	40 g	40%	⑨ Vacuum seal and cook sous vide in **90** °C / **194** °F bath for 1 h.
			⑩ Freeze-dry as above.
Hon-shimeji mushrooms, tops	100 g	100%	⑪ Freeze-dry as above.
Scallions, greens only, fine julienne	100 g	100%	

(2009)



For more on how to assemble these components to make Astronaut Ramen, see page 5·247.

EXAMPLE RECIPE

RAMEN STOCK POWDER

Yields 38 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Japanese stock see page 296	300 g	100%	① Combine and vacuum seal.
Chinese everyday stock see page 296	250 g	83%	② Cook sous vide in **60** °C / **140** °F bath for 1 h.
			③ Strain.
			④ Heat broth to **85** °C / **185** °F.
Scallions, whites only, thinly sliced	10 g	3.3%	
Kombu	6 g	2%	
Smithfield ham, thinly sliced	6 g	2%	
Garlic, finely minced	5 g	1.7%	
Dried scallop (store-bought)	4 g	1.3%	⑤ Add to simmering broth.
Bonito flakes (katsuobushi)	2 g	0.7%	⑥ Steep for 10 s.
White soy sauce	to taste		⑦ Strain.
			⑧ Season.
			⑨ Freeze-dry by using the table on page 450.
			⑩ Grind into powder.

(2009)

CRYOGENIC FREEZING AND CARBONATING

Liquid nitrogen has long been a must-have commodity in research laboratories, where it is used for numerous cooling tasks. Recently, it has become a staple in Modernist kitchens.

For more on the long and interesting history of liquid nitrogen use in the kitchen, dating back more than a century, see page 1·60.

There is no official acronym or abbreviation for liquid nitrogen, but many people use LN2, which is short for "liquid N_2." In principle, the abbreviation ought to have a subscript, but in email and internet postings it is invariably just LN2.

Liquid nitrogen provides a quick way to make food extremely cold. In a sense, it is the opposite of deep-frying, which uses a hot liquid such as fat or oil to heat and cook food.

Most cooking is about adding heat to food in order to cause chemical reactions in that food that can change its color, taste, and texture. But one can also cook by removing heat. If we remove enough heat, we can freeze the food, turning liquids into solids. The most common example is that water turns to ice. But oil, alcohol, and other food-related liquids all freeze.

In fact, at low enough temperatures, *every liquid can freeze solid*. Even the gases in the air around us can do so, although most of them become a liquid first. This was first realized in the 19th century, when scientists discovered the main elements in air—nitrogen and oxygen—could be liquefied. In doing so, they invented the field of **cryogenics**, which is generally defined as the production of temperature below −150 °C / −238 °F.

The term cryogenics comes from the Greek words for "the production of freezing cold," and that is a good description. Cold liquids, called **cryogens**, are the primary tool of cryogenics, and the most commonly used cryogen is liquid nitrogen. Air is mostly nitrogen (about 78%), so it is present all around us. Indeed, nitrogen is the most common pure elemental substance on Earth. Nitrogen is useful as a cryogen because it has a boiling point of −196 °C / −321 °F and a freezing point that is just slightly lower at −210 °C / −346 °F. In between those temperatures, nitrogen is a clear, thin liquid that is not chemically reactive.

Plunging things in liquid nitrogen is an ideal way to drop their temperature, for two reasons. The first is obvious: the temperature is incredibly low. The rate at which heat flow occurs depends on the temperature difference (see Heat in Motion, page 1·277), and with liquid nitrogen, you can obtain stunningly high temperature differences—over 200 °C / 360 °F. Heat will flow rapidly out of anything immersed in liquid nitrogen—much more rapidly than with ice.

Surprisingly, you would actually need to use a larger mass of liquid nitrogen than you would with ice! Due to the factors discussed on the next page in How Liquid Nitrogen Boils, this cryogen is not particularly good at bulk chilling. It actually absorbs less energy than ice does.

Liquid nitrogen excels in cooking applications where you need extremely low temperature to, for example, freeze alcohol or to make a soft substance as hard and brittle as glass. The cryogen is also good at producing extremely high rates of cooling—for example, to freeze drops of liquid instantly so they stay spherical or to make instant ice cream. In those applications, liquid nitrogen truly seems magical.

Cooking with Liquid Nitrogen

Modernist cooks have learned to use liquid nitrogen to create unexpected food textures. These freezing agents make possible novel foods, such as ice creams with ultrafine textures and deep-fried pork roast that is succulent on the inside with perfectly crisped skin on the outside.

Liquid nitrogen helps pull off that last feat, known as **cryosearing,** because it creates a difference of about 400 °C / 720 °F between the frigid outer layers of the frozen meat and the searing-hot oil in a fryer. The heat in the oil thaws, cooks, and starts crisping the skin well before it begins working in earnest on the frozen and chilled flesh beneath.

To make supersmooth ice cream, add liquid nitrogen to a mixer containing an ice-cream base.

THE SCIENCE OF

How Liquid Nitrogen Boils

Liquid nitrogen absorbs heat much faster than ice-water does, but if you need to chill a large amount of food, you'll need a lot more liquid nitrogen to do the job than you would if you used an ice bath. Liquid nitrogen is just not that efficient as a bulk chilling agent.

The main reason this is true is that boiling a liquid takes a lot of energy—the so-called latent heat of vaporization (see page 1·314). Nitrogen has a fairly low latent heat of 200 kJ/kg (86 BTU/lb). So to turn 1 kg / 2.2 lb of liquid nitrogen at −196 °C / −321 °F into nitrogen gas at the same temperature, it must absorb 200 kJ / 190 BTU of energy.

That absorbed energy contributes greatly to the cooling, but compared to the energy needed to boil other liquids, it isn't very impressive. It is less than 10% as much as is needed to boil water—2,260 kJ/kg (972 BTU/lb).

Water has a large latent heat because hydrogen bonds cause water molecules to stick to each other; it takes energy to overcome those bonds. The boiling point of water is so much higher than that of liquid nitrogen for the same reason.

The latent heat of vaporization for liquid nitrogen is only about two-thirds as high as the latent heat of fusion for ice—334 kJ/kg (144 BTU/lb)—which means that boiling 1 kg / 2.2 lb of liquid nitrogen takes less energy than melting the same amount of ice. So if you want to measure the total energy removed on a per kilogram basis, ice wins over liquid nitrogen.

Another area where nitrogen loses is in specific heat. Once the nitrogen turns to gas, it has a specific heat of 1 kJ/kg (0.4 BTU/lb), compared to liquid water at 4.18 kJ/kg (1.8 BTU/lb).

The final way in which liquid nitrogen comes up short is that, when it boils, the gas expands by a factor of 175 and bubbles away from the surface being cooled, escaping before it can fully transfer heat.

If you want to chill 20 l / 5 gal of veal stock at 90 °C / 194 °F down to 5 °C / 41 °F, you could do it by pouring in some liquid nitrogen. Or you could add ice (in a plastic bag to prevent dilution). But you'll need fewer kilograms of ice than of liquid nitrogen.

Olive oil dipped in liquid nitrogen turns solid and can be cut with a knife.

For more on how to cryosear pork roast or duck breasts, see page 3·124.

For more on how the speed of freezing affects ice crystal growth, see page 1·304.

For more on dry ice and sublimation, see page 1·326.

The water freezes very rapidly into many tiny ice crystals that are much smaller—and less perceptible in the mouth—than the fewer, larger crystals that form during conventional freezing.

Another culinary use for liquid nitrogen is a riff on what science-inspired entertainers or chemistry professors do when they freeze a rose or a rubber ball in the cold liquid, then smash the brittle result into shards, as if it had been transformed into glass. Cooks can similarly use liquid nitrogen to freeze, say, olive oil into a brittle solid. You can then shatter, crumble, or distribute it as you like; as it warms, it melts back into puddles of delicious liquid. Maple syrup and honey lend themselves to the same kind of treatment—for instructions, see How to Cryoshatter, page 463.

Some uses for liquid nitrogen are just plain fun. Cryofreeze a fruit meringue, then pop it in your mouth. Fog will emerge, dragon-like, from your mouth and nose—but be sure to read the safety warnings on page 464 before trying this.

Once you become comfortable with liquid nitrogen, the temptation to try it with just about every food can be hard to resist. For example, we like to break up cryogenically frozen raspberries into individual drupelets and garnish a salad with them or fold them into a pastry filling, which can produce a tartlet that doesn't leak juice until the first bite (see page 462).

If you freeze fresh herbs in liquid nitrogen, they become easy to grind into powders that have a consistency just like commercial bottled herbs yet without losing their freshness. Indeed, almost anything that you might want to grind into a puree can be frozen, shattered or powdered this way (see How to Cryopowder, page 461). The same freeze-and-shatter technique, for instance, can markedly change the appearance of beef tartare on the plate.

Liquid nitrogen makes quick work of many kinds of *mis en place*. Shucking oysters is as easy as spraying the frigid liquid onto the mollusk's hinge; the oyster just pops open (a trick we learned from chef Homaro Cantu). Dip tough nuts, such as chestnuts, in liquid nitrogen for a second, and you can shatter their shells with a tap of a mallet.

Frost glasses like a pro by pouring a little liquid nitrogen into an empty glass and swirling it around; the water vapor in the air instantly condenses into frost on the cooled glass. (Make sure the glass is completely dry or it may shatter!) Liquid nitrogen is also great for chilling alcoholic cocktails without diluting them with ice, a technique that might be especially apt for preparing Halloween party drinks that bubble and fume eerily, for example. And making gin-and-tonic slushies on a sweltering summer day sounds like another appealing application for liquid nitrogen.

Dry Ice

Carbon dioxide is another common gas generated by many living things. Humans exhale about 1 kg / 2.2 lbs of carbon dioxide per day. The physics of carbon dioxide at low temperature is a bit different than nitrogen—instead of turning into a liquid, it becomes a solid, known as dry ice, at a temperature of −78 °C / −173 °F (see page 1·304). This is warmer than the usual definition of cryogenics but still cold enough that it can be used as a kitchen cryogen.

THE SOURCES OF

Cryogens for Sale

Industrial gas suppliers like Praxair sell liquid nitrogen, but first you need a Dewar flask to put it in. A 50 l / 13 gal Dewar flask is probably the minimum size of a storage container that is useful for a moderately busy kitchen. Smaller containers lose too much to evaporation and require too-frequent refills.

The easiest approach for commercial kitchens is to contract with a supplier that leases the Dewar vessels and makes weekly deliveries to top them up. Call a major industrial gas supplier first because they can refer you to a local supplier if they don't offer this service themselves.

Dry ice is typically sold in 1 kg / 2 lb blocks or bags of pellets, and it is easier to come by than liquid nitrogen. In the U.S., many urban supermarkets stock dry ice. One approach is to call freight shipping companies near an airport for a referral; dry ice suppliers often set up shop close to such shippers.

COOKING WITH LIQUID NITROGEN

Liquid nitrogen has no flavor of its own, and it will not dilute foods. It boils at −196 °C/ −321 °F, and with the proper safety precautions, you can add it to sweet wine and fruit juice to make sorbet or instantly freeze droplets of custard into tiny beads of ice cream. Shards of shattered, frozen salmon make an intriguing tartare. Quique Dacosta makes faux truffles by freezing clouds of Parmesan foam, then dusting them with mushroom powder. After being doused in the stuff, oysters, clams, or hard-shelled nuts open effortlessly, and artisanal hams can be shaved paper-thin.

We and other cooks also sometimes use liquid nitrogen when cooking sous vide. For example, after slow-cooking a pork roast to perfection in a water bath, you can quickly freeze the exterior, then flash-fry or sear it at very high heat to brown and crisp the skin without altering the meat below—see page 5·17 for more detailed instructions. Fresh vegetables, such as beets and asparagus, blanch perfectly after they have been frozen with liquid nitrogen and then thawed.

Never dip dense foods in liquid nitrogen and then serve them immediately, or you will experience the culinary version of licking a pump handle in midwinter. Fingers, lips, and taste buds will freeze to foods that are dense or high in water content, causing nasty frostbite.

CULINARY STRATEGIES FOR USING LIQUID NITROGEN

Application type	Application	Typical use	See page
breaking	cracking or shucking	nuts, shellfish	
	grinding or milling	nut meat	
		grain flour	3·377
	powdering	fresh herbs and spices	461
		meat and seafood tartare	3·62
	shattering	berry cells, citrus fruit, onion, root vegetables	462, 463
		meat and seafood for forcemeats	
	shaving	bacon shaving, ham shaving	461
cooking	cryofrying	chicken crown, pork roast	5·113, 3·126
	cryosearing	duck breast	3·124
forming	custards	ice cream beads	next page
	meringues	egg foam, pectin foam, methylcellulose foam	4·291
	solid fats	molded butter, olive oil slushy	next page
texturing	freeze-blanching	asparagus, beets, corn, onions, peas	3·374

Extreme care should be taken when working with liquid nitrogen. Before using it, please review the safety tips on page 464.

HOW TO Cryopoach

Deep-frying is about putting food into a hot liquid to make it hard and crispy. Ironically, putting food into a bath of liquid nitrogen can accomplish something analogous—the extreme cold will freeze the food from the outside in, giving it a hard, frozen crust. By analogy to poaching in hot water, we call this cryopoaching. With a food that has poor thermal conductivity, such as a foam, the outside will freeze hard before the inside does, so a quick cryopoach will make a hard, frozen crust. Or, for complete freezing, let the food sit in the liquid nitrogen.

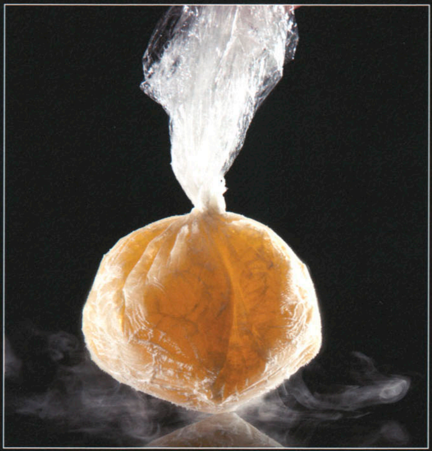
1 **Submerge item into liquid nitrogen.** The liquid nitrogen bath should ideally be deep enough to completely cover the food. If cryopoaching a liquid, you can dispense from a plastic bottle or piping bag to form droplets. If you drop from a height of 30–46 cm / 12–18 in, most liquids will form nice round droplets, then freeze into spheres.

2 **Use a perforated spoon or sieve to lift the food out, and strain off the nitrogen.** Remove small pieces from the bath very quickly unless you want them to freeze all the way through.

3 **Temper in a freezer before serving (not shown).** Caution: do not serve cryopoached foods directly from the liquid nitrogen treatment; the extreme cold can cause injury. The exceptions to this rule are foams that have been poached for no more than 15 seconds, which may be served immediately. For an example recipe of a cryopoached foam, see page 5·165.

VARIATION: Cryopoaching an Oil

1 **Gather plastic wrap to make a pouch and pour oil into it.** Tie off the the plastic wrap tightly.



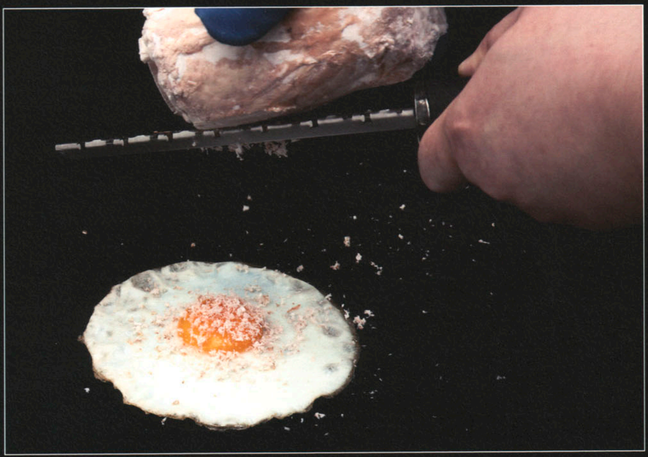
2 **Immerse the plastic-wrapped pouch in liquid nitrogen until it freezes.**

Frozen oil can also be cryoshattered into beautiful glass-like shards.

3 **Remove the plastic wrap.** If immersed for a short time, the center will still be liquid. If done for longer, it will freeze solid.

HOW TO Cryograte

Imagine being able to finely grate porcini mushrooms, bananas, smoked ham hocks, or other soft foods.
Use the gratings to enrich a recipe, or sprinkle them on the plate as an unexpected garnish.



1 **Cryopoach until frozen solid (see previous page).**

2 **Remove from liquid nitrogen when food is solid and glassy; handle with tongs or a thick, insulated glove.** Don't touch the frozen food directly because it is cold enough to cause frostbite.

3 **Use a microplane or bonito shaver to grate to desired flake size.**

4 **Refreeze and repeat as needed.** As the food thaws, it will become progressively more difficult to grate cleanly.

HOW TO Cryopowder

Cryopowdering is the very best way to grind herbs very finely without mashing them into a paste.
The technique also works for flower petals and many vegetables.

1 **Freeze leaves by pouring liquid nitrogen over them.**

2 **Grind frozen herbs in a blade-style coffee grinder.** You may need to add a little extra liquid nitrogen to keep the leaves frozen while grinding. The powder thaws very quickly.

HOW TO Disassemble Fruit with Liquid Nitrogen

Once certain fruits, such as citrus and berries, are frozen with liquid nitrogen, we can easily and precisely dissect them along their natural fracture lines to create perfect segments. Shattering also lends a dramatic presentation to foods that fragment in irregular pieces, such as beets (see page 3·374). This technique for separating fruit segments was patented in 1961 by Robert Webster and Elmer Parish; the patent has since expired.

Cryoshattered blackberries, made famous by Ferran Adrià of elBulli, make an intriguing snack when served plain, in a salad, or as a picturesque garnish. For a recipe using cryoshattered pomelo sacs, see Thai Crab Miang, page 5·189.

For important safety precautions to observe when using liquid nitrogen, see page 464.

1 **Put berries in a porcelain mortar.**

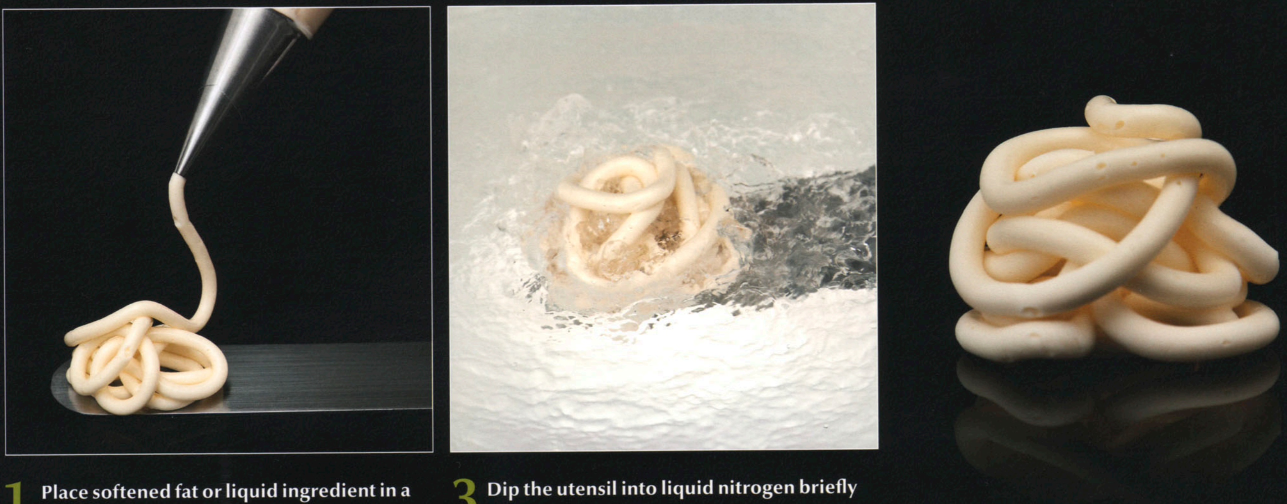
2 **Cover with liquid nitrogen.** Allow the liquid nitrogen to boil away completely.

3 **Shatter.** Use a pestle or the back of a wooden spoon to lightly press on the berries and separate them into individual drupelets.

4 **Thaw for a few minutes before serving.**

HOW TO Cryoshape

Create dynamic and unexpected shapes and presentations by extruding or layering food into liquid nitrogen. This technique works especially well with softened fats or viscous liquids.



1 **Place softened fat or liquid ingredient in a piping bag or squeeze bottle (not shown).**

2 **Squeeze a ribbon of the food onto a palette knife or spatula to form the desired shape.**

3 **Dip the utensil into liquid nitrogen briefly to set.**

4 **Temper (not shown).** Cryoshaped foods must be tempered in a freezer or refrigerator before serving to avoid inducing injury from extreme cold.

Instead of putting it onto a spatula, you can also squirt, spray, splatter, drip, or drizzle liquid food directly into liquid nitrogen, where it will freeze into interesting shapes. Retrieve the results with a slotted spoon. Maple syrup is a good example.

HOW TO Cryoshatter

Liquid and soft foods such as soft cheeses don't normally shatter, but they do when frozen in liquid nitrogen. The shards can be used for special effect. Shards of frozen liquids can be served solid but will transform on the plate into little puddles as they thaw.

1 **Cryopoach the food by dipping it in liquid nitrogen until frozen completely through.**

2 **Remove using tongs and insulated gloves (not shown).**

3 **Strike sharply with a mallet or other utensil to shatter.** Wear safety glasses and long sleeves to prevent bits of ultracold food from hitting your eyes or skin.

4 **Arrange on plate and temper, or thaw for use in recipes.** Cryopoached foods must be tempered in a freezer or refrigerator before serving to avoid inducing injury from extreme cold.

Carbon dioxide is often known by its chemical formula, CO_2.

Carbon dioxide is soluble in water (see page 1·330) and this is the basis for **carbonation**, the name for the process of dissolving carbon dioxide in a food, most often a beverage like soda pop, seltzer, or Champagne.

The temperature of a carbonated liquid affects how quickly it goes flat. Carbon dioxide is soluble in water, and the colder the water, the more carbon dioxide can dissolve in it. Even a little warming or a small reduction of the pressure above the liquid—which happens suddenly when you pop open a Champagne bottle—and the gas bubbles out. That's why you should keep carbonated liquids chilled. Take care not to freeze them, however, because ice can't hold the carbon dioxide.

Any container of carbon dioxide will also have air in the headspace above the carbon dioxide. You must vent that air-rich gas before carbonating food—otherwise, you will be trying to carbonate with mostly air instead of mostly carbon dioxide, and it won't work. To avoid this problem, allow the gas cylinder to vent to the atmosphere for a few minutes, or depress the valve momentarily while charging with a gas cartridge.

Kitchen carbonation of liquids is fairly straightforward for liquids and can even be done with solid foods. One approach requires a pressurized tank of carbon dioxide. An industrial-size tank equipped with a pressure regulator, like those used by bars and taverns, works well. So do small, disposable cartridges of the kind used in seltzer dispensers.

An alternative technique uses dry ice, which packs molecules of carbon dioxide together in an extremely compact arrangement. When the solid **sublimes** directly into a gas (without melting en route), it expands in volume by a factor of more than 500. So it doesn't take much dry ice to carbonate a batch of food or beverage. A little over 3 g / 0.1 oz of dry ice—just a few pebble-size pieces—can transform 355 ml / 12 oz of water into seltzer.

Soda water has been around for centuries. The early American chemist Joseph Priestley made a name for himself, in part, for dissolving "fixed air," an early term for carbon dioxide, into water.

Because food is mostly water, cooks can also carbonate it by dissolving the gas into the water contained in the food. The technique even works for fruits with peels, including grapes, oranges, and bananas (see How to Carbonate Fruit, page 472).

If you are so inclined, you can serve carbonated bananas that look and feel normal (though they must be served cold) but taste like a solid banana soda. The same trick works for oranges, whose carbonated versions put orange pop to shame. Bite on a carbonated grape and it goes down fizzing and crackling. You can even carbonate meat.

What happens to the carbon dioxide in drinks you consume? Many people are surprised to find out that it almost immediately diffuses through the gut wall and is absorbed into the blood, then transported to the lungs. You typically exhale the CO_2 within a minute of swallowing it.

Novel and exciting as this approach may be, not all foods are tasty when made fizzy. Many people associate fizziness in strawberries and cucumbers, for example, with unwanted fermentation and spoilage.

Beyond carbonation, dry ice is also a fine substitute for liquid nitrogen when cryosearing some meats and poultry.

Safe Handling of Cryogens

Dry ice and liquid nitrogen can be fabulous tools in the kitchen, but they are seriously cold substances, so they can be dangerous. Cryogens can injure cooks and their guests alike. Serious mishandling can even have fatal consequences. Much of the hazard arises from people's unfamiliarity with supercold materials, but just like the well-known perils posed by extremely hot temperatures in the kitchen, those associated with cryogens can also be minimized by safe handling.

In our kitchen, we use the same precautions when working with liquid nitrogen as when working with hot frying oil; indeed, the two are almost polar opposites. Liquid nitrogen happens to be almost the same number of degrees below the freezing point of water, at −196 °C / −321 °F, as deep-frying oil is above it, at 200 °C / 392 °F. In some ways, however, liquid nitrogen is actually safer than frying oil. Droplets of liquid nitrogen will often bounce harmlessly off skin due to the Leidenfrost effect (see page 1·317); frying oil certainly won't. Liquid nitrogen also can't catch fire the way oil can.

The guiding principle you should follow to protect eaters is this: no dry ice or liquid nitrogen should still be in a dish or drink when it is served. Cooks use similar precautions when preparing dishes with hot oil. Fortunately, liquid nitrogen usually flashes out of a food well before it's ready for presentation at the table.

Nevertheless, it's fun to immerse food in liquid nitrogen and eat it almost right away. Doing so is truly safe, however, only with dry foods, such as marshmallows and meringues. In those cases, the foam structure insulates the food so that only a thin surface layer is frozen. That layer thaws quickly on your tongue, rather than freezing to it. Foods that contain a lot of moisture should never be consumed right after immersion in liquid nitrogen.

Cooks and others in the kitchen must respect the potential dangers of contact with liquid nitrogen. Safety goggles are a must, and wearing porous fabrics, such as canvas shoes, is not advised. Liquid nitrogen spilled on clothing could

Dry ice emits cold carbon dioxide gas, which is cooler than the dew point of the ambient air. This creates a cold fog that people can mistake for smoke. Dry ice is a good source of carbon dioxide for carbonating fruit, such as this mandarin.

THE SCIENCE OF

The Taste of Fizziness

The distinct, multisensory experience of imbibing a carbonated drink is more than just a matter of tiny bubbles of carbon dioxide popping on your tongue. The fizzy feel involves our touch and pain response systems. But there is also biochemistry at work.

In late 2009, a team of neuroscientists reported in the journal *Science* that they had teased out some of the details of the familiar experience by silencing specific populations of sensory cells in taste buds, such as sour-sensing cells and sweet-sensing cells, one by one. They showed that sour-sensing cells are the ones that respond to carbonation.

This observation could help explain why seltzer, or soda water, seems to taste sour. Investigating the process at the molecular level, these researchers found that the sensation begins when an enzyme (carbonic anhydrase 4) on the surface of the tongue converts carbon dioxide into ions of bicarbonate and hydrogen. The hydrogen ions then trigger the taste bud receptors, which report a sour taste to the brain.

The researchers speculate that the evolutionary purpose of our ability to sense carbon dioxide might be to detect spoiled, fermenting foods. On the other hand, the capability might be a fortuitous side effect of the presence of the enzymes involved, whose primary role is to maintain the pH of taste buds.

Once scientists arrive at a definitive answer to that question, perhaps they can figure out why the Nigerian miracle berry, *Synsepalum dulcificum,* nullifies the taste of carbonation. A fizzy consumed after eating the fruit tastes oddly flat.

A dramatic illustration of why you should take care when using dry ice in enclosed spaces occurred in Cameroon in 1986. Carbon dioxide had been building up for years in the deep, cold waters of Lake Nyos when suddenly, early one morning, the supersaturated water released its gas in a foaming fountain within the lake. This is analogous to opening a Champagne bottle and having its contents spurt out. Because carbon dioxide is denser than air, the cloud of gas displaced the air near the ground as it swept over adjacent farms and a village. Some 1,700 people and 3,500 livestock suffocated in the tragedy.

Liquid nitrogen will run off any impermeable convex surface due to the Leidenfrost effect (see page 1·317). This includes human skin. A few drops dribbled over the back of your hand poses no danger. But don't try this with a cupped hand!

Believe it or not, an infamous party trick for chemists and physicists is to gargle small amounts of liquid nitrogen. Although many people do it without harm, it can also cause serious injury if done incorrectly.

soak into the fabric weave, which would hold it against the skin long enough to cause severe frostbite.

It is essential to avoid doing dumb things such as pouring liquid nitrogen from above eye level or bending over next to a coworker who is pouring it. The cryogen swiftly chills metal containers or implements to dangerous temperatures. So always wear gloves when working with cryogens.

Dry ice and liquid nitrogen both turn to gas when exposed to heat. In a poorly ventilated space, this can be hazardous. As an example, if you tipped over a Dewar flask of liquid nitrogen in a small room or in a car, the gas could displace enough air in the room that you wouldn't be able to breathe. Normal air contains 21% oxygen, but a rapid influx of vaporized nitrogen can dilute this concentration to below 16%, the point at which people start to lose consciousness. Oxygen levels below 16% can even cause death by asphyxiation.

Dry ice can endanger users in a similar fashion, but it vaporizes much more slowly—which is why dry ice has long been used, quite safely, in theatrical performances to produce fog. Most injuries from dry ice occur from handling it directly, without tongs or gloves, or by accidentally eating some that is hidden in a dish that was prepared with dry ice before it had the time to sublime into the air.

Liquid nitrogen greatly expands as it evaporates, so you must *never seal it in a container*—evaporation will cause the pressure to build up until the container explodes. Liquid nitrogen Dewars have either loose-fitting lids or special pressure releases to vent the gas so that this does not occur.

Further Reading

Adrià, F., et al. *A Day at elBulli: An Insight Into the Ideas, Methods and Creativity of Ferran Adria*. Phaidon Press, Incorporated, 2010.

Adrià, F. *elBulli 1994-1997*. Ecco, 2006.

Adrià, F. *elBulli 1998-2002*. Ecco, 2005.

Adrià, F. *elBulli 2003-2004*. Ecco, 2006.

Adrià, F. *Modern Gastronomy: A to Z*. CRC Press, 2009.

Achatz, G. *Alinea*. Achatz, 2008.

Aduriz, A. L. *Clorofilia*. IXO Editorial, 2004.

Aftel, M., Patterson, D. *Aroma: The Magic of Essential Oils in Foods and Fragrance*. Artisan, 2004.

Blumenthal, H. *The Fat Duck Cookbook*. Bloomsbury USA, 2009.

Bras, M. *Essential Cuisine*. Ici La Press, 2002.

Buchi Literature. *The Kjeldahl Guide – A guidance for your daily laboratory work*. BÜCHI Labortechnik AG, 2010.

Buchi Literature. *The Laboratory Assistant*. BÜCHI Labortechnik AG, Switzerland, 2007.

Coyne, G. *The Laboratory Companion: A Practical Guide to Materials, Equipment, and Technique*. Wiley-Interscience, 2005.

Cross Media, editor. *Dashi and Umami: The Heart of Japanese Cuisine*. Cross Media, 2009.

Fellows, P.J. *Food Processing Technology: Principles and Practice*. CRC Press, 2009.

Gayler, P. *The Sauce Book: 300 World Sauces Made Simple*. Kyle Books, 2009.

Kamozawa, A., Talbot, A. H. *Ideas in Food: Great Recipes and Why They Work*. Clarkson Potter, 2010.

Kunz, G., Kaminsky, P. *The Elements of Taste*. Little, Brown & Company, 2001.

Norman, J., editor. *Herbs & Spices: The Cook's Reference*. DK Publishing, Inc., 2002.

Shugar, G., Ballinger, J. *Chemical Technicians' Ready Reference Handbook*. McGraw-Hill Professional, 1996.

Sokolov, R. *The Saucier's Apprentice: A Modern Guide to Classic French Sauces for the Home*. Alfred A. Knopf, 1976.

Thompson, R. B. *Illustrated Guide to Home Chemistry Experiments*. O'Reilly Media, 2008.

Ziegler, H. *Flavourings: Production, Composition, Applications, Regulations*. Wiley-VCH, 2007.

The Curious Cook. curiouscook.com

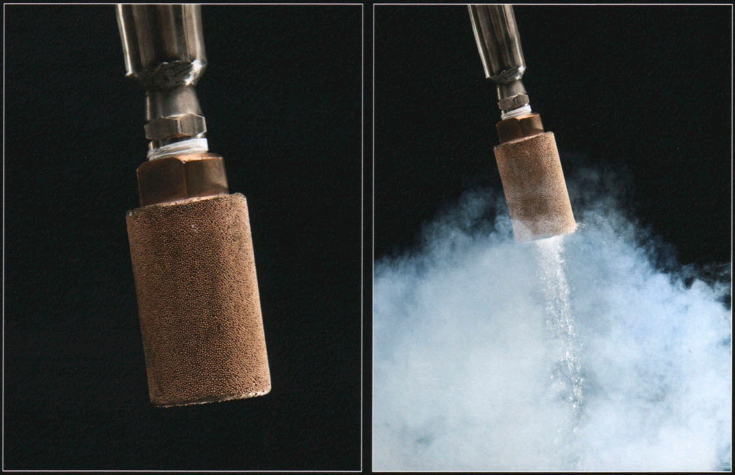
Ideas in Food. ideasinfood.com

Cooking Issues. cookingissues.wordpress.com

THE SAFETY OF

Handling Liquid Nitrogen

Liquid nitrogen is typically stored in large Dewar vessels that have a pressurized dispensing system (left). When the valve is turned, liquid nitrogen pours out of the nozzle end and ideally into smaller dewar or container (bottom). Be aware that the metal parts of the dispensing system can become extremely cold, so do not touch them without wearing cryogenic gloves. Many people assume that you need gloves to prevent liquid nitrogen from spilling on your hands. Although skin contact can be a concern, you are more likely to get a frostbite injury from touching a piece of metal that has been chilled by liquid nitrogen.



Liquid nitrogen can be dispensed by pouring or, for large Dewars, by using a special dispensing system.

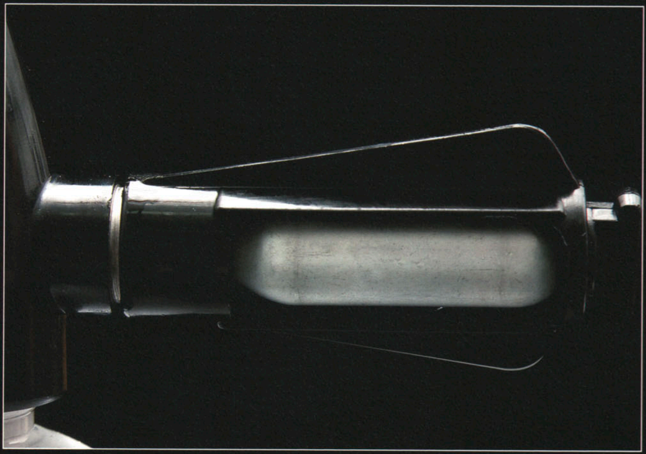
HOW TO Carbonate a Liquid

Making fizzy drinks is easy enough, but to get a really good carbonation, you need three cartridges and a few tips.

1 **Chill the liquid and the siphon (not shown).** Carbon dioxide is only truly soluble in cold liquids.

2 **Pour the cold liquid into the siphon.** Do not overfill. A 1 l / 35 oz siphon should have no more than 750 ml / 25 oz of liquid in it. Follow manufacturer's guidelines.

3 **Attach the siphon head.**



4 **Hold the nozzle down while engaging the first cartridge (not shown).** This blows out the residual air from the headspace of the siphon.

5 **Load with two more cartridges.** For best results, store the loaded siphon in the refrigerator for an hour before serving so that the gas fully dissolves into the liquid.

HOW TO Carbonate Fruit

We're all familiar with the most common type of consumable carbonation, the fizzy soda. The bubbles in such a beverage come from carbon dioxide, which dissolves into the liquid under pressure during bottling and reemerges in gaseous form to produce the characteristic fizz when we open the can and relieve the pressure.

A similar process can add a temporary but lively boost to fruits. If you put fruit in a pressure chamber with carbon dioxide, the gas will permeate the skin and dissolve into the juice inside.

Neurobiologist Galen Kaufman patented a process for doing this in 1997, and he put the patent up for sale on eBay for $10 million. When the patent didn't sell, he started a company, Fizzy Fruit, which began test-marketing the product as a way to entice children to adopt better eating habits. Does this patent mean chefs can't carbonate fruit without buying a license from Kaufman? This book cannot give legal advice; the authors can, however, make a few observations. Kaufman's U.S. patent holds force only within the United States. Our reading of the patent suggests that it covers carbonating fruit and then packaging it to retain the carbonation. Directly serving carbonated fruit out of the same chamber used to carbonate it—as a restaurant might do—appears not to be covered by the patent.

Chef Homaro Cantu often serves carbonated grapes, which he calls "Champagne grapes."

1 **Chill fruit.** The fruit must be ice-cold.

2 **Wet fruit and place in carbonation chamber (not shown).** You can use a siphon or a soda keg. Size the fruit pieces to fit inside.

3 **Add liquid (optional).** Adding grape juice to apples, for example, will infuse the apple with carbonated grape juice.

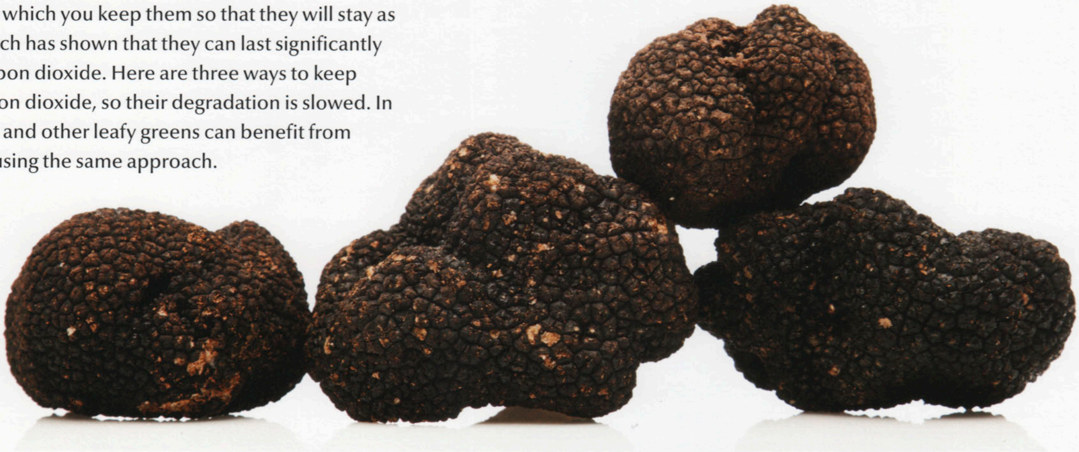
4 **Charge the chamber.** If using a siphon, use three carbon dioxide cartridges. For a soda keg, charge to at least 2–2.8 bar / 30–40 psi. Be sure to leave a vent open while filling so that the air inside is replaced by carbon dioxide.

5 **Carbonate.** Hold, refrigerated, long enough for gas to dissolve into the food. Exact time will vary with the size and wetness of the food; grapes will be ready in about 3 h. An unpeeled orange will need to sit overnight.

6 **Serve chilled.** Serving on ice will extend the potency of carbonated grapes to about 20 min. Larger fruits will stay fizzy longer.

HOW TO Preserve the Freshness of Truffles

Fresh truffles are so expensive that it is well worth the time and effort to modify the environment in which you keep them so that they will stay as pristine as possible. Research has shown that they can last significantly longer if stored in pure carbon dioxide. Here are three ways to keep truffles in a blanket of carbon dioxide, so their degradation is slowed. In addition to truffles, lettuce and other leafy greens can benefit from storage in carbon dioxide using the same approach.



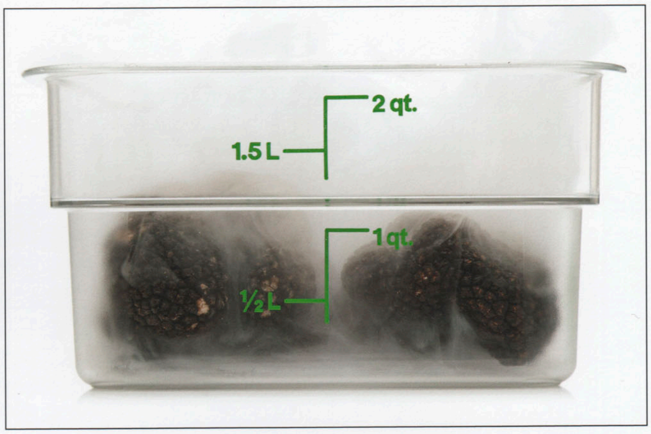
1 **Place the truffle in a partially sealed, resealable bag or storage container.**

2 **Load a carbon dioxide cartridge in a completely empty, dry soda siphon (not shown).**

3 **Blow the carbon dioxide into the container to flush out the oxygen.**

4 **Seal and store in the refrigerator.** Repeat each time you use the truffle.

VARIATION: Storing with Dry Ice



1 **Place a pea-size piece (~3 g / 0.1 oz) of dry ice in a plastic resealable container.** Do not use glass.

2 **Place the truffle in the container so that it will not touch the dry ice and be damaged by the extreme cold.**

3 **Let the carbon dioxide sublimate for a few minutes with the lid resting loosely on the container, then seal and refrigerate.**

Pressure may build up in the container. This is not a problem; just release the pressure and reseal.

VARIATION: Storing by Using a Gas-Flushing Vacuum Sealer

1 **Seal the truffle loosely with carbon dioxide in a gas-flushing, chamber-style vacuum sealer, then refrigerate.**

EXAMPLE RECIPE

ORANGE SODA

Yields 340 g

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Navel orange juice see page 352	300 g (from 700 g of oranges)	100%	① Centrifuge at 27,500*g* for 1 h. ② Strain through fine sieve.
Fructose	30 g	10%	③ Combine with juice, and reserve.
Phosphoric acid	2 g	0.67%	
Gum arabic	5 g	1.67%	④ Blend together until smooth.
Water	2 g	0.67%	⑤ Add 1.5 g of emulsion to sweetened juice, and refrigerate remaining emulsion for later use.
Orange essential oil	0.12 g (about seven drops)	0.04%	⑥ Hand-blend juice until smooth. ⑦ Strain through fine sieve. ⑧ Transfer to soda siphon, and charge with two carbon dioxide cartridges. ⑨ Refrigerate soda in siphons for at least 2 h before serving.

(2010)

For other methods of clarifying juice, see page 352.

HOW TO Carbonate Fruit with Dry Ice

Many people have created fizzy fruit by accident in thermal coolers kept cold by dry ice. For a more controlled version, follow these steps. Leave the skins and peels on fruit. It works well for apples, oranges, grapes, and even bananas. Never use a glass container to carbonate fruit, the air pressure may cause it to shatter.

1 **Put a layer of crushed dry ice in the bottom of a plastic, sealable container.** Remember to use all safety procedures when handling dry ice.

2 **Place an insulating layer of paper towels or a clean, dry tea towel on the ice layer.** This protects the fruit from the extreme temperature of the dry ice.

3 **Put the cold fruit on the insulating layer.** Let the dry ice and fruit settle a few minutes so that the "steam" pushes out the oxygen in the container.

4 **Seal container.** The lid may pop off a couple of times due to a buildup of air pressure. That's fine. Just put the lid back on.

5 **Let the fruit carbonate.** This will take only 30 min for small fruits like grapes and overnight for larger, whole fruits like apples and oranges. Longer carbonation times require refrigeration.


1


3


5

EXAMPLE RECIPE

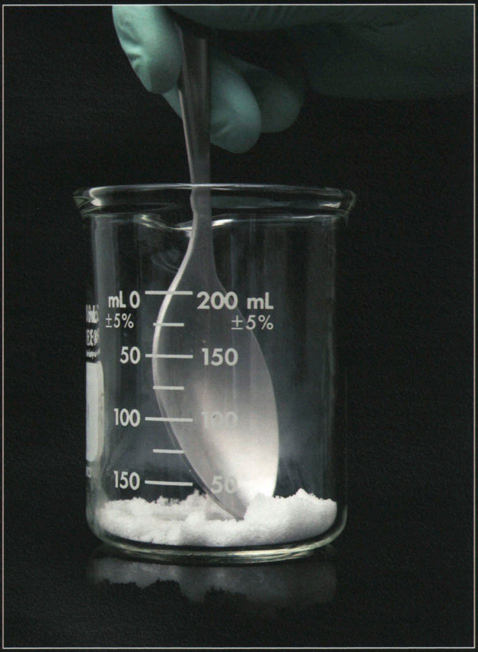
STRAWBERRY MILK SHAKE ADAPTED FROM JUAN MARI ARZAK

Yields 1.2 kg

INGREDIENT	QUANTITY	SCALING	PROCEDURE
Strawberries, washed and trimmed	1 kg	167%	① Arrange in one layer, and dust with fructose. ② Freeze. ③ Thaw at room temperature. ④ Puree. ⑤ Strain through fine sieve and reserve 600 g of strawberry juice.
Fructose	400 g	67%	
Skim milk	600 g	100%	⑥ Disperse powders in milk. ⑦ Bring to a simmer, and remove from heat. ⑧ Cool.
Sweet whey powder	12 g	2% *(1%)**	
Locust bean gum (Tic Gums brand)	1.2 g	0.2% *(0.1%)**	
Strawberry juice, from above	600 g	100%	⑨ Blend cooled milk into reserved juice.
Dry ice	100 g	16.7%	⑩ Crush dry ice in blender to fine powder. ⑪ Divide evenly among four glasses. ⑫ Pour 200 g of milk shake into each glass. Wait 10 s; milk shakes will bubble over. ⑬ Serve alongside our Mushroom Swiss Burger (see page 5·11).

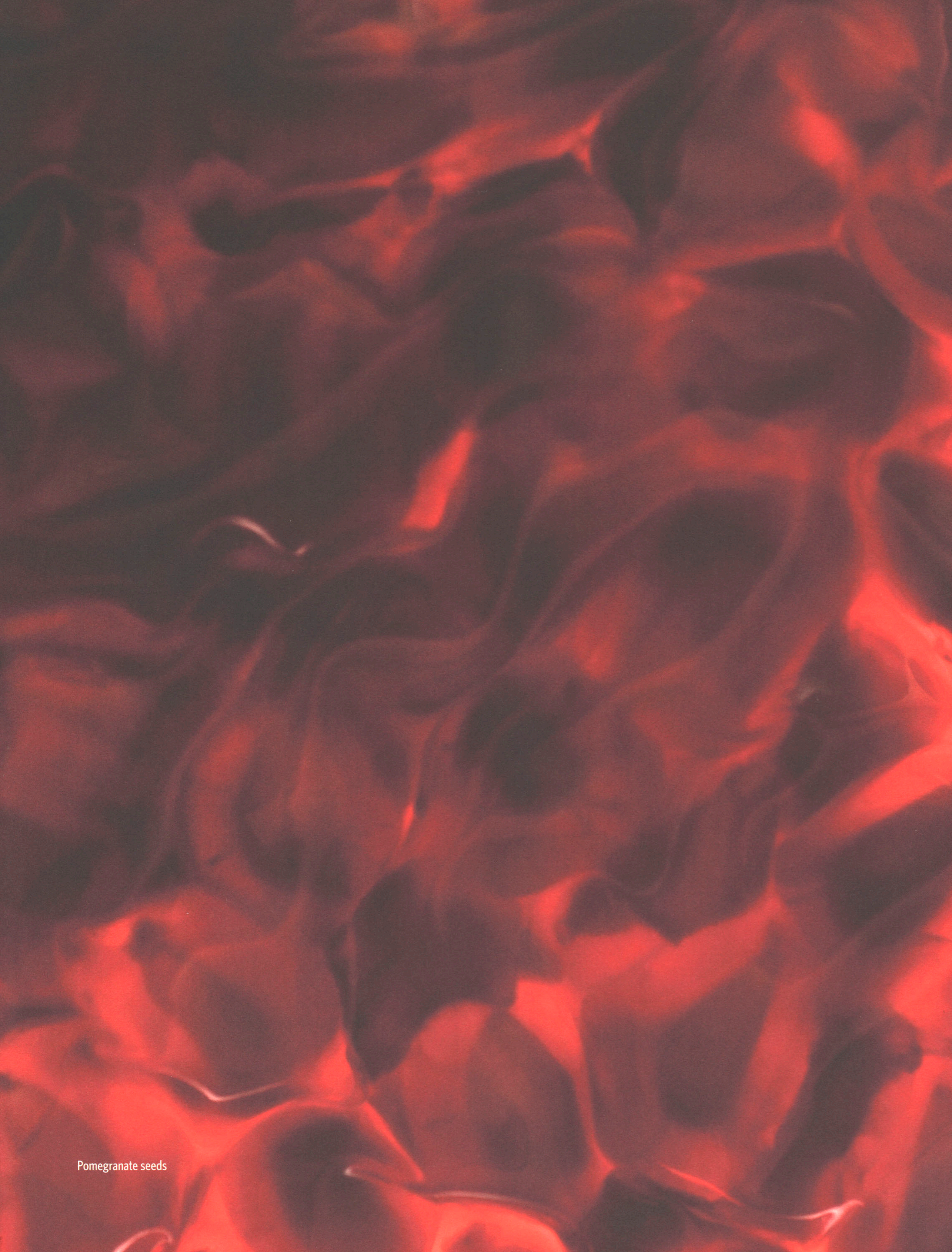
(published 2009, adapted 2010)

(% of total weight of the strawberry juice and milk*)



Make certain that all dry ice has sublimated before serving.

Navy beans



Pomegranate seeds